CRANFIELD UNIVERSITY

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MODELLING OF TILT ROTOR MISSION PERFORMANCE TO ASSESS ENVIRONMENTAL IMPACT

SCHOOL OF ENGINEERING
MSc by Research

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Academic Year: 2011 - 2012

Supervisor: Professor Howard Smith
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ABSTRACT

New technologies and new rotorcraft operations are being developed in order to meet new environmental requirements such as noise reduction and less pollutant emissions.

In this project a parametric study was developed over a tilt rotor model in order to assess the environmental impact in terms of operational parameter and fuel burned looking at pollutant emission released into the air such as NO_x, CO, UHC, PM, CO_2 & H_2O

In order to perform the study previously stated, a computational tool build on Simulink titled tilt rotor mission performance was developed to run a single mission profile as a base line making different operational variations on every mission segment looking at deviations over fuel burned and pollutant emissions.

The contribution of pollutant emissions during the cruise segment was compared to other phases obtaining 80% of CO_2 and H_2O, 75% of CO and UHC, 77% of NO_x, and 78% of PM. Also, comparing the distance flown of the tilt rotor with some turboprop aircraft, it was found that the fuel burned and levels of CO_2 are higher using tilt rotor rather than turboprop aircraft. On the other hand this is much better than helicopters.

Keywords:

Rotorcraft, Mission Level, Atmosphere, Pollutant Emissions, Model.

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LIST OF ABBREVIATIONS

ACARE	Advisory Council for Aeronautics Research in Europe
ACRP	Airport Cooperative Research Program
BE	Blade Element
BEMT	Blade Element Momentum Theory
CAMRAD	Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics
EI	Emissions Index
EPA	Environmental Protection Agency
EPNL	Effective Perceived Noise Level - dB
FAA	Federal Aviation Administration
FOCA	Federal Office of Civil Aviation
HESCOM	Helicopter Sizing and Performance Computer Program
ICAO	International Civil Aviation Organization
IPCC	intergovernmental panel on climate change
ISA	International Standard Atmosphere
MT	Blade Element Momentum Theory
NASA	National Aeronautics and Space Administration
NDARC	NASA Design and Analysis of Rotorcraft
OGE	Out Ground Effect
SFC	Specific Fuel Consumption
SHP	Shaft Horsepower
SL	Sea Level
SPL	Sound Pressure Level
TAS	True Air Speed
TOGW	Takeoff Gross Weight
VTOL	Vertical Takeoff and Landing

LIST OF SYMBOLS

A_r	Rotor Area	ft^2
A_b	Rotor Blade Area	ft^2
AR	Aspect Ratio	
b	Number of blades	
b_w	Wing Span	ft
B	Tip losses	
bhp	Brake Horsepower	hp
$\overline{C_{do}}$	Blade drag coefficient	
C_{do}	Parasite Drag Coefficient	
C_L	Lift Coefficient	
CO	Carbon Monoxide	
CO_2	Carbon Dioxide	
c_b	Rotor Blade Chord	ft
C_T	Thrust Coefficient	
d	Observer Distance	ft
D	Drag Force	lb
D_f	Fuselage Drag	lb
DL	Disk loading	lb/ft^2
e	Oswald Number	
E	Endurance	hr
f	Equivalent Flat Plate Area	ft^2
f_{Peak}	Peak Frequency	Hz
H_2O	Water Vapour	
K_i	Induced Power Required Factor	
K_μ	Profile Power Required Factor	
L	Lift Force	lb
NO	Nitric Oxide	
NO_2	Nitric Dioxide	
NO_x	Oxides of Nitrogen	
P_c	Climb Power	hp

P_i	Induced Power	hp
PM	Particulate Matter	
P_{of}	Profile Power	hp
P_p	Parasite Power	hp
P_R	Power Required	hp
P_T	Total Power	hp
q	Dynamic Pressure	lb/in^2
Rr	Rotor Radio	ft
R	Range	nm
S	Wing Area	ft^2
T	Thrust	lb
UHC	Unburned Hydrocarbons	
V	Velocity respect to the air	ft/s
V_T	Rotor Tip Speed	ft/s
W	Gross Weight	lb
W_C	Carbon Atomic Weight	g
W_i	Initial Weight	lb
W_f	Final Weight	lb
W_O	Oxygen Atomic Weight	g
x	Number of Atoms of Carbon	
y	Number of Atoms of Hydrogen	

GREEK SYMBOLS

ρ	Air Density	slugs/ft^3
μ	Advanced Ratio	
σ	Rotor Solidity	
∞	Free Stream Conditions	
θ	Nacelle Angle	deg
φ	Elevation Angle	deg
η	Efficiency	
Ω	Rotor Rotational Speed	Rad/s

SUBSCRIPTS

150	150 meters
500	500 feet
H	Hover
Prop	Propeller or Prop rotor
v	Vertical

1 INTRODUCTION

Currently, Rotorcraft operations are been concentrated on small activities such as rescue and evacuation, corporative missions, aerial surveillance among other which represents a few percentage of the global air transport. However, taking into account the rapidly increase of aircraft operations it is imperative to prepare for the next decade because a growth it is expected between 2 up to 3 times just on rotorcraft civil operations.

These current and future operational increments have a direct negative impact on the environment in terms of noise generation and pollutant emissions caused by fossil fuels use which produce global warming and greenhouse effect.

1.1 Influence of Aviation on Environment

First of all, Global aviation has and is growing very fast in order to cover the passenger's needs. Indeed, economically it is a worthy business. However, this fast rise affects enormously the environment specifically the air quality on the atmosphere and neighbourhoods around airports.

Civil aviation moves around 2 billion passengers annually; this amount represents a big number of flights to and from main airports around the world contributing to climate change increasing (CO_2, NO_x, CO, H_2O) levels in accordance with the intergovernmental panel on climate change (IPCC, 1999).

These levels affect the chemical balance of the atmosphere causing a change in the net radiation; this variation is a metric called radioactive forcing (RF) (Gössling and Upham, 2009). Radiation variation affects the way how efficiently the Earth keeps or rejects the heat which is radiated from the sun.

CO_2 emissions produce global warming, NO_x emissions affect the atmospheric chemistry creating tropospheric O3 as a result, global warming happens, H_2O Vapour affects clouds formation, thus, cause global warming as well. Also, global warming brings other issues such change in weather patterns (i.e. precipitations, winds, temperatures, etc.)

1.2 Rotorcraft in Civil Aviation

Rotorcraft, especially helicopters, represents a minor activity with the trend to increase at least two times during the next ten years. As a huge movement of passengers is expected, time is a key factor in order to move people from one airport to another, but reducing connection times between main airports toward towns is an aim that aviation is looking for. Thus, a good way is rotorcraft which could provide a shuttle service from cities or town heliports to airports, up to cities without airports or small ground infrastructure.

Also, new technologies and new aircraft operations are being developed in order to meet new environmental requirements such as noise reduction, less pollutant emissions global and locally. Tilt rotors which are able to operate with or without runways, fly faster than helicopters but it carries fewer payloads are being studied if is a good complement to turboprop aircrafts to feed main airports from other.

1.3 Overview

Clearly, protecting the environment affects all global aviation because aircraft and rotorcraft are one of the main contributors of environmental degradation. The advisory council of Aeronautical Research in Europe (ACARE, 2008) has established some targets in order to reduce and look after the environment in ten years' time; those targets are related to CO_2, NOx and noise reductions, asking manufactures and others entities to improve and produce new technologies or solutions.

In the rotorcraft field some innovative designs are being studied try to produce less pollutant emissions and noise. In this particular case tilt rotors are one of those solutions. Unfortunately, this kind of solutions takes a while to be implemented; however it is possible making some mathematical models in order to predict what would be emissions and noise production when a tilt rotor is operating.

By time, some simulation tools have been developed with the aim of design and evaluate helicopter performance, but no one of them evaluates emissions and noise at mission level.

Some of these tools are NDARC (NASA design and Analysis of Rotorcraft) (Johnson, 2010), CAMRAD II (Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics) (Johnson, 1988), HESCOMP. (The Helicopter Sizing and Performance Computer Program) (Davis,S. J. ; Rosenstein,H. ; Stanzione,K. A. ; Wisniewski,J. S., 1979).

1.4 Project Objectives, Scope and limitations

The aim of this research project is to assess the environmental impact when a tilt rotor is in service in terms of fuel consumption and noise emission at a mission level.

It will be necessary to develop a computational tool based on Simulink in order to calculate mission fuel requirements by the power needed on each part of the proposed mission as a baseline. Then, different operational parameters are analysed over a mission profile in order to determine the environmental impact in terms of fuel burned along with its pollutant emissions and noise.

Also, the project conduct a parameter study in order to find the best way to operate a tilt rotor looking for minimum pollutant and noise emissions. Also, equations used in some modules of this model are presented in low fidelity level and for steady state.

The tilt rotor mission performance model could be assembled on a multidisciplinary framework to evaluate new possible technologies such as innovative engines or new components.

It is required to clarify that currently tilt rotors are grouped for military service or tests. Therefore, this research is limited to all information found in the public domain. Thus, Tilt rotor Model 300 (Refer to appendix E) was selected to carry out this study and a hypothetical base line mission profile (i.e. Corporative) was proposed.

1.5 Thesis Structure

This thesis is organized by chapters in which chapter 2, titled literature review presents an outline of helicopter and airplane performance knowledge needed to understand a tilt rotor as well as emissions and noise. Chapter 3 brings descriptions about different models created along with the interaction with each other.

Results and discussion in chapter 4 presents parametric study results using the full model.

Finally, in chapter 5 and 6 conclusions and recommendations for future work are presented.

2 LITERATURE REVIEW

Tilt rotor is a rotorcraft which shares performance characteristics of helicopters in low speed flight along with turboprop airplanes in high speed flight.

In these types of machines the engine nacelles rotate out at the wing tips, providing the facility and manoeuvrability for Vertical take-off and landings (VTOL); once airborne, after tilting its nacelles forward like turboprop airplane it can operate faster. These characteristics give them good performance such as high speed, long range and endurance which are very useful in civil and military missions (Carlson and Zhao 2004).

2.1 Performance – Airplane mode

"Performance is a term used to describe the ability of an airplane to accomplish certain things that make it useful for certain purposes" (FAA-H-8083-25A, 2008), those purposes are: take-off and landing, rate of climb, ceiling, payload, range, speed, and fuel economy.

In general terms the aircraft performance is the evaluation of each part of a proposed mission profile in terms of power required and power available looking at the suitably of being complied with.

With this aim, one way to evaluate the performance is by equations of motions but just for an unaccelerated and level flight conditions called static performance (Anderson, 1999).

2.1.1 Performance in cruise

This kind of performance evaluation is done by measuring and comparing the power required and power available for a given speed, altitude and ambient conditions determined by ISA. Additionally some geometrical characteristics used as inputs are necessary to do this.

To find power required it is useful to know that exists two parts, or terms, called parasite power and induced power.

$$P_R = q_\infty S C_{D0} V_\infty + q_\infty S V_\infty \frac{C_L^2}{\pi e AR} \quad \textbf{(2-1)}$$

In which the first term $[q_\infty S C_{D0} V_\infty]$ corresponds to parasite power required due to zero-lift drag coefficient $C_{D0,}$ it means power to overcome airframe drag, q_∞ corresponds to dynamic pressure which is $q_\infty = \frac{1}{2}\rho V_\infty^2$. The second term is the induced power required due to induced lift $q_\infty S V_\infty \frac{C_L^2}{\pi e AR}$ where lift coefficient is $C_L = \frac{L}{1/2 \rho V_\infty^2 S}$. (Anderson, 1999)

Power available is the power provided by the engine better known (Brake shaft horsepower) for turbo prop airplanes multiply by the prop rotor efficiency represented with:

$$P_A = \eta_{Prop} * bhp \quad \textbf{(2-2)}$$

When power available and power required are plotted together it is possible to determine maximum speed where both lines are intersecting (Anderson, 1999)

Since the tilt rotor behaviour is similar as a propeller driven airplane, it is possible to determine the range that means (to cover longest distance) and endurance (to stay on the air for the longest time). But, first of all, it is necessary to take into account the engine characteristics such sfc (specific fuel consumption) which is a critical factor that influences range and endurance because it is the weight of fuel consumed per unit power per unit time (Anderson, 2005).

The way to determine range flown is using Breguet's range equation (Raymer, 2006)

$$R = \frac{\eta_{Prop}}{c} \frac{L}{D} ln\left(\frac{W_i}{W_f}\right) \quad \textbf{(2-3)}$$

In which the terms involved are prop rotor efficiency η_{Prop} , sfc, Lift to drag ratio and the ratio between final weight W_f and initial weight W_i in cruise.

To determine endurance a similar equation exists from Breguets. (Raymer, 2006)

$$E = \frac{\eta_{Prop}}{c} \frac{L^{3/2}}{D} (2\rho_{\infty} S)^{1/2} \left(W_f{}^{-1/2} - W_i{}^{-1/2} \right) \quad \textbf{(2-4)}$$

In which the terms involved are prop rotor efficiency η_{Prop} , sfc, Lift to drag ratio, final weight W_f and initial weight W_i in cruise.

2.2 Performance – Helicopter mode

In this type of analysis the tilt rotor has more steps or phases in its mission profile like take off which is performed from Hover state, climb, and forward flight and descent.

For a tilt rotor, where the rotors are spaced apart and not overlapping, it is possible to calculate the performance of one rotor and multiply by two. The assumption that each rotor carries half of the vehicle weight in hover is a good one, In forward flight is necessary to have in mind that the wings help the tilt rotor reducing the thrust needed, However, the fuselage drag has its contribution as well but increasing the thrust.

It is necessary to assess the rotor power required; different methods exist to determine the power needed such Blade Element or Momentum Theory, Momentum Theory and a mix called Blade Element Momentum Theory (BEMT).

Blade element theory (BET) uses forces that act on each single segment of each blade (Figure 2-1); these forces and moments are aerodynamics, thus, each element is considered as a single profile section (Figure 2-2) in which it is necessary to evaluate forces; this method is more accurate compare with (MT) but needs many data to be used (Leishman, 2006).

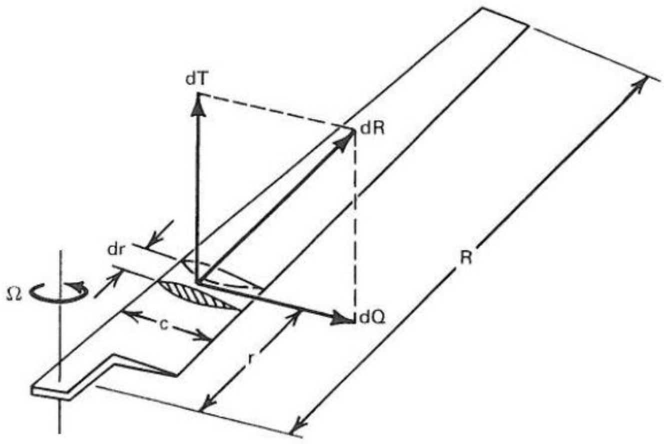

Figure 2-1 Single profile segment element (Layton, 1984)

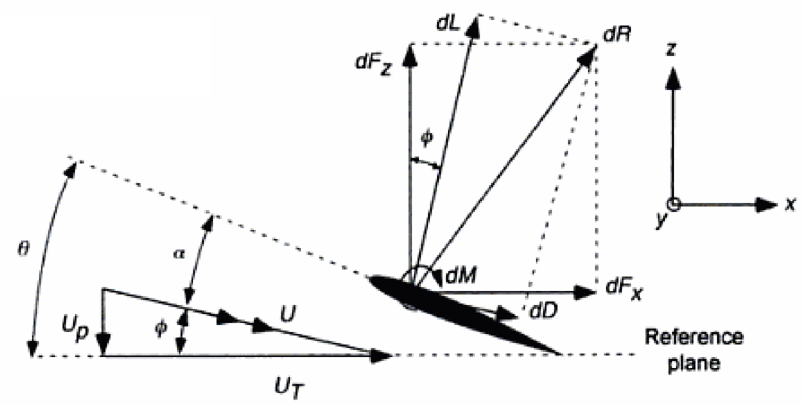

Figure 2-2 Aerodynamic environment at a blade element (Leishman, 2006)

Momentum theory (MT), instead, postulated originally by Froude (1889) is the flow through a thin disc with infinite number of blades which change pressure and velocity on a virtual stream tube (Layton, 1984). (Figure 2-3)

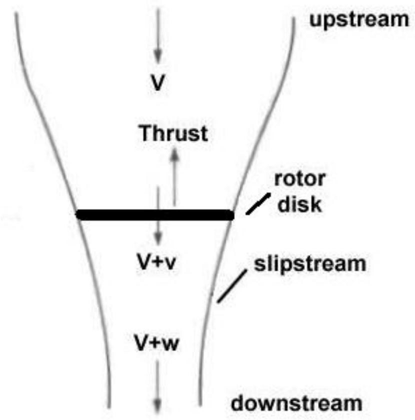

Figure 2-3 Stream tube of flow through a rotor

Taking into account the previous descriptions momentum theory will be performed because it has a good approximation and less data required.

Since it was described before about what performance means, for helicopter mode the power required from hover to reach maximum speed in helicopter mode can be found by the following equation:

$$P_R = P_i + P_{of} + P_p \quad \textbf{(2-5)}$$

In which each item represents Induced power, Profile Power and Parasite Power; induced power is the power required to produce the lifting thrust, Profile power is the power to overcome rotor torque and finally parasite power is to overcome fuselage drag (Layton, 1984).

Each element will be explained in following sections.

2.2.1 Hover performance

In this condition the tilt rotor is not flying at specific forward speed because is cero, it is steady at specific altitude and ambient conditions. In this condition the thrust is equal to the weight following the second Newton's Law.

At this point the Power required is defined by a term called induced velocity v_{iH}, which is due to the pumping action of each rotor to carry the weight.

$$v_{iH} = \sqrt{\frac{T}{2\rho A_r}} \quad \textbf{(2-6)}$$

Where T is Thrust force and A_r is rotor disc area.

Additionally, some losses exist by the rotor tip called tip loss *B* which is defined by the vortex generated for each rotor blade tip. This value is between 0.95 and 0.98 (Leishman, 2006).

$$B = 1 - \frac{\sqrt{2C_T}}{b} \quad \textbf{(2-7)}$$

Where *b* is the number of blades installed on each prop rotor and C_T is the Thrust coefficient depending on rotational rotor speed V_T.

$$C_T = \frac{T}{A_r \rho V_T^2} \quad \textbf{(2-8a)}$$

$$V_T = \Omega * R_r \quad \textbf{(2-8b)}$$

Where Ω the rotor's rotational velocity and *Rr* is the rotor's radio.

The induced Power needed in Hover State to overcome the weight is

$$P_i = T.v_{iH} \quad \textbf{(2-9)}$$

The following part that makes an additional contribution to find the total power in Hover is Profile power to overcome the rotor torque due to drag and move it through the air.

$$P_{of} = \frac{1}{8}\overline{C_{do}}\rho A_b V_T^3 = \frac{1}{8}\overline{C_{do}}\rho\sigma A_r V_T^3 \quad \textbf{(2-10a)}$$

$$\sigma = \frac{b * c_r}{\pi * R_r} \quad \textbf{(2-10b)}$$

Where solidity σ is driven by *b* number of blades, c_r blades chord and *Rr* blade radius.

This expression in equation 2-10a is defined by $\overline{C_{do}}$ that is average blade drag coefficient, A_b blade area or A_r rotor area and σ solidity. This last one means the fraction of disc area which is composed of blades (Layton, 1984).

Finally, to find the total power in Hover is

$$P_{TH} = \frac{T}{B}\sqrt{\frac{T}{2\rho A_r}} + \frac{1}{8}\overline{C_{do}}\rho\sigma A_r V_T^3 \quad \textbf{(2-11)}$$

Comparing power required and engines power available at this moment, it is possible to find performance capabilities such service ceiling and exceed power that is useful to determine rate of climb.

2.2.2 Forward flight performance

Since the tilt rotor flies from hover into forward flight depending on mission segment, the total power required changes considerably, due to the effects of forward velocity on the rotors and drag produced by the fuselage (Figure 2-4).

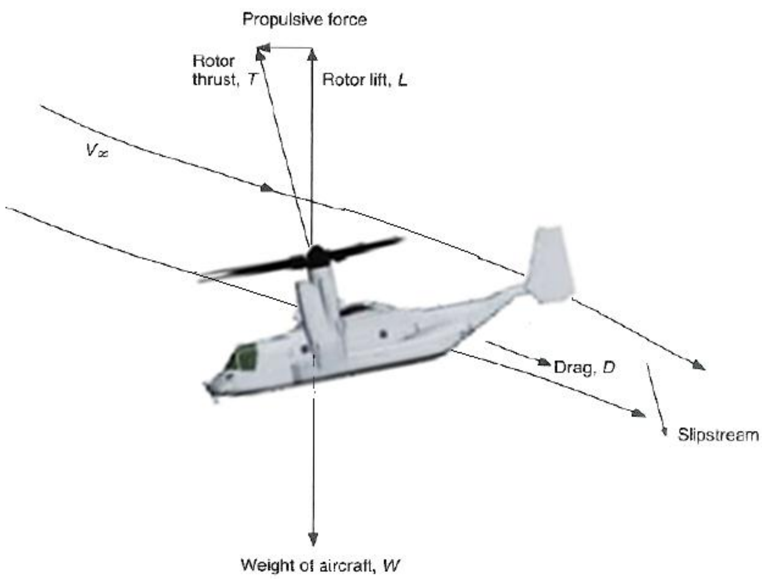

Figure 2-4 Velocity and force due to forward flight

Also, the lift produced by the wings help the rotors decreasing its thrust requirement; however, part of the drag affects directly this benefit.

As it was stated before power required is the sum of various power required to overcome: Rotor induced drag, rotor profile drag and fuselage parasite drag.

In this case the previous formulas used in hover have to be modified in order to evaluate the power required on different forward speeds. Thus, some correction factors exist to be added in induced power and profile power required called induced (*Ki*) and profile (*K*μ) correction factors.(Layton, 1984)

$$K_i = \sqrt{-\frac{\left(\frac{V}{v_{iH}}\right)^2}{2} + \sqrt{\left(\frac{V^2}{2{v_{iH}}^2}\right)^2 + 1}} \qquad \textbf{(2-12)}$$

Where, the term V corresponds to Horizontal speed and v_{iH} induced velocity previously explained in equation 2-6.

$$K_\mu = 1 + (4.3\mu^2) \qquad \textbf{(2-13)}$$

The value 4.3 is a factor which can vary from 4.3 to 5 for normal helicopters and μ is called advance ratio corresponding on Forward speed over tip blades speed V/V_T; if this ratio is too high, profile power becomes higher by effects of compressibility, radial and reverse flow (Leishman.2006)

Taking into account these factors, the equations to induce power and profile power will become,

$$P_i = K_i \frac{T}{B}\sqrt{\frac{T}{2\rho A_r}} \qquad \textbf{(2-14)}$$

$$P_{of} = \frac{1}{8}\overline{C_{do}}\rho\sigma A_r V_T^3 K_\mu \qquad \textbf{(2-15)}$$

These correction factors are useful in hover state and vertical climb, because if forwards speed comes to cero K_μ and K_i will be 1.

The last term that is necessary to add in order to analyse forward flight is Parasite power P_p in which the main factor that turns this values higher or not is airframe flat reference area *f* , hence,

$$P_p = \frac{1}{2}\rho(V^3)f \tag{2-16}$$

At the end, the total power required in forward flight condition is,

$$P_T = K_i \frac{T}{B}\sqrt{\frac{T}{2\rho A_r}} + \frac{1}{8}\overline{C_{do}}\rho\sigma A_r V_T^3 K_\mu + \frac{1}{2}\rho(V^3)f \tag{2-17}$$

In addition, performance capabilities like rate of climb, service ceiling, speed and range are possible to be calculated using power available.

2.2.3 Helicopter climb performance

In this performance state climb power needed to overcome gravitational force at specific rate of climb is defined by

$$P_c = TV_v = WV_v \tag{2-18}$$

Where, T thrust is equal to operational weight *W* and V_V is the vertical speed chosen to reach any altitude desired (Leishman, 2006). However, it is better use this equation summing all previous powers to measure climb in forward flight.

2.2.4 Conversion performance

It is important to recall that the main characteristic of any tilt rotor is the facility to transform itself from double rotor helicopter to a turbo prop airplane.

To measure power required in each part of transition corridor, it is important to know the nacelle angle, by this way it is possible to find the thrust required in each nacelle position angle, but some restriction exist depending on blade tip speed and forward speed Figure 2-5.

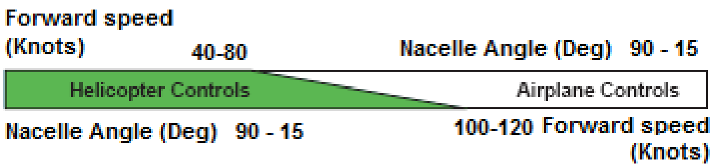

Figure 2-5 Nacelle and speed regimen

In each nacelle angle power requirements are different from Hover helicopter mode up to Cruise airplane mode, a graphical representation comparing helicopter mode (90 deg) and Airplane mode (0 deg) are shown in Figure 2-6.

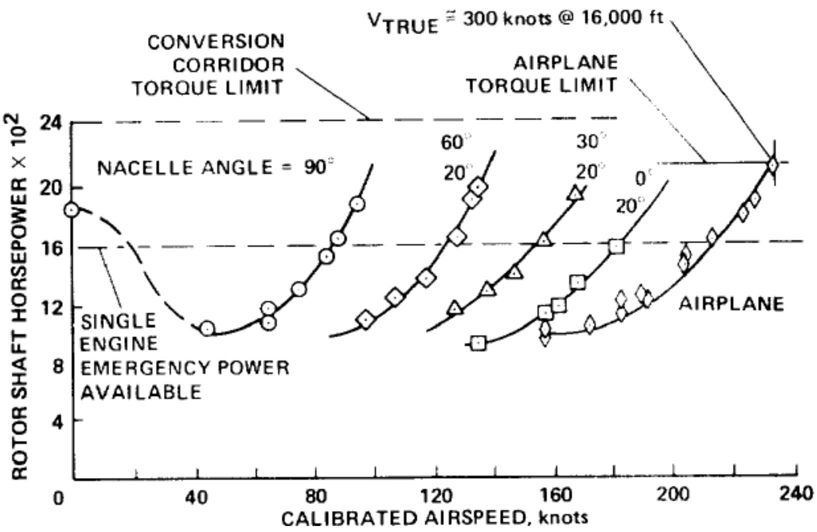

Figure 2-6 Power required Vs Speed for XV-15 tilt rotor in different flight modes (Churchill, 1982)

Where the helicopter curve coming through different nacelle angles up to 15 deg are described by

$$P_T = K_i \frac{T}{B}\sqrt{\frac{T}{2\rho A_r}} + \frac{1}{8}\overline{C_{do}}\rho\sigma A_r V_T^3 K_\mu + \frac{1}{2}\rho(V^3)f \qquad \textbf{(2-19)}$$

In which each term were presented previously with a change on thrust term, because this term will change in terms of nacelle angle as follows,

$$T = \sqrt{(W-L)^2 + {D_f}^2} * \sin(\theta) \quad \textbf{(2-20)}$$

Where, θ corresponds to nacelle angle, *W* is tilt rotor weight, *L* is wing lift and D_f Drag due to airframe area.

2.3 Pollutant Emissions

The engines installed on a rotorcraft, in this particular case a tilt rotor are responsible for the pollutant emissions that are released into the air through the exhaust. These emissions are the results of the combustion process taking place inside the combustor.

Depending on the location of this pollutants whether on ground or not, they have different effects local or globally. The emission species are carbon dioxide (CO_2), water vapour (H_2O), oxides of nitrogen (NOx), carbon monoxide (CO), unburned hydrocarbons (UHC) and Particulate matter (PM). (Coutinho, 2008)

The production of these elements is directly related to temperature and combustion times, and the temperature that is related to power needed depending on operational conditions as well. Also chemical characteristics of the fuel used. (Lefebvre and Ballal, 2010)

One of the main parameters to measure the emissions are directly related to particular factor called Emissions index (EI) which is defined as the correlation of produced grams of a distinct pollutant to kilograms of fuel burned. Another way to measure emissions is by stoichiometric balance used on CO_2 and H_2O (Coutinho, 2008).

2.3.1 Carbon Dioxide (CO_2) and Water Vapour (H_2O)

These species are one of the most contributing elements to global warming. Those are a product of the complete combustion process and only depend on the fuel rate used. The only route to mitigate its production is by mean of other non-fossil fuels in the combustion. (Rolls-Royce, 2005)

In order to calculate the EI, it is necessary to know the fuel chemical structure; in this case Jet-A with chemical composition ($C_{11}H_{22}$). (Dagaut, 2008) that will be used.

(Coutinho, 2008) shows a method to calculated CO_2 and H_2O EI taking into account atomic weight and atom numbers

$$EI_{CO_2} = \frac{x(W_C + 2W_O)}{xW_C + yW_H} \quad \textbf{(2-21)}$$

$$EI_{H_2O} = \frac{\frac{y}{2}(2W_H + W_O)}{xW_C + yW_H} \quad \textbf{(2-22)}$$

Where, y corresponds to the number of hydrogen atoms and x the number of atoms of carbon shown on the fuel chemical formula. In this particular case EI's for CO_2 and H_2O are 3160_g/kg and 1230_g/kg.

2.3.2 Carbon Monoxide (CO)

Known to be highly toxic and by produce of acid rain this sub-product of the combustion process is release into the air when there is not enough oxygen to allow formation of CO_2, called incomplete combustion. It is an issue for aero-engines in low-power rating and it is a common gas produced by road transport.

Federal Office of Civil Aviation (FOCA, 2009) presents a methodology using different rotorcraft shaft power data in which some formulas based on shaft horsepower are shown in order to get emissions index

$$EI_{CO}\left[\frac{g}{kg}\right] = 5660(SHP)^{-1.11} \quad \textbf{(2-23)}$$

In order to find the emission is necessary to multiply EI with fuel burned

$$Emissions\,[g] = EI\left[\frac{g}{kg}\right] * Fuel\ Burned\,[kg] \quad \textbf{(2-24)}$$

2.3.3 Oxides of Nitrogen (NOx)

Being toxic and one of acid rain factors NOx are divided in two species: Nitric oxide (NO) and nitric dioxide (NO_2). Those elements are formed from the heat inside the combustion chamber, if temperature increases the quantity of NOx increase. This is released into the air and can be carried for long distances causing health issues

Also, there are three additional types of NOx generated from the combustion process Thermal (NOx), Prompt (NOx) and Fuel (NOx) according to (Rolls-Royce, 2005).

Emission index from (FOCA, 2009) for NOx is

$$EI_{NOx}\left[\frac{g}{kg}\right] = 0.2113(SHP)^{0.5777} \qquad \textbf{(2-25)}$$

2.3.4 Particulate Matters (PM)

Particulate matters are composed of soot and smoke which are other products from combustion process. They are a mixture of microscopic solids, particles and liquid drops. Also these kinds of matters are responsible for cirrus clouds and contrails which produce global warming and greenhouse effect. (IPCC, 1999; ACRP, 2008)

Emission index from (FOCA, 2009) for PM

$$EI_{PM}\left[\frac{g}{kg}\right] = -4.8\times10^{-8}(SHP)^2 + 2.3664\times10^{-4}(SHP) + 0.1056 \qquad \textbf{(2-26)}$$

2.3.5 Unburned Hydrocarbons (UHC)

The last residual components are emitted at low power levels, as a result of nozzle defects, different burning rates and low temperatures. Also, UHC are responsible for acid rain formation. (ACRP, 2008)

Emission index from (FOCA, 2009) for UHC

$$EI_{UHC}\left[\frac{g}{kg}\right] = 3819(SHP)^{-1.0801} \qquad \textbf{(2-27)}$$

2.4 Rotorcraft Noise

It is well known that noise is another pollutant even though it cannot be taste, smell or see; noise is consider a disturbing sound that becomes unwanted when it interferes with normal life such sleeping. Also, noise affects people's health including stress, high blood pressure, and speech interference and hearing loss according to the environmental protection agency (EPA).

The noise generated by any rotorcraft is produced by different mechanical sources included rotors, turboshaft engines and accessory gears. A measure of noise is expressed in decibels (dB) and it is called Effective perceived noise level (EPNL). This measure is used for subjective judgments studies in order to rate the annoyance or noisiness caused by industrial, road traffic and aircraft noise.(Bell Helicopter, 1969)

The International Civil Aviation Organization (ICAO) has emitted a test procedure to issue noise certifications to rotorcraft using different measure points. This process is done when a helicopter is already manufactured. (Annex 16 ICAO, 1993)

2.4.1 Noise generated by Rotor

To determine the noise produced by rotors it is important to clarify that different aerodynamic noise are generated called Rotational noise, blade slap and vortex noise or broadband noise.(Johnson, 1980)

Rotational noise will generate from the pressure field around the rotor that change periodically relative to a stationary observer. It is thumping sound depending on blade frequency becoming in bangs on high ones. This noise is significant compared to other noises mainly at high advancing tip speed in helicopter mode or measure from large distances. Calculate this noise is not worthy because the tilt rotor in commercial operation doesn't flight at high speed in helicopter mode. (Faulkner, 1974)

Blade slap noise is neglected because depends on forwards and high speed helicopter mode flight, thus it has the same consideration previously stated.

Vortex Noise represents the main noise source related to rotor and it is produced by random fluctuations of blade forces and tip vortices.

Overall sound pressure level (SPL) developed by schlegel (cited in Faulkner, 1974) is useful to predict vortex noise at 300 feet from observer on a side line

$$L_P = 10log_{10}\left(\frac{7.62 \times 10^{-10}(T^2)\left({V_{tip}}^2\right)}{\rho^2 A_b}\right) \quad \textbf{(2-28)}$$

Where L_P Pressure level is in function of T thrust, V_{tip} rotor tip sped and A_b rotor blade area.

However, it is necessary to transform this pressure noise into perceived noise level that corresponds to human aural system

$$L_{PN} = L_P + 3.0 - 0.000375 \times d \quad \textbf{(2-29)}$$

Where, d corresponds to observer distance greater than 2000 feet.

To measure the perceive noise at different distance the peak frequency is added

$$f_{Peak} = \frac{V_{tip}}{b_c} \quad \textbf{(2-30)}$$

$$L_{PN} = L_P + 3.0 - 0.000375 \times d + 0.0264 \times f_{Peak}\left(1 - \frac{d}{2000}\right) \quad \textbf{(2-31)}$$

The distance attenuation is a dilution of the sound energy by spreading over large spherical surface areas from the source increases. So, if 300 feet is taken as standard distance, the energy levels at different distances are reduced 6 dB per double of distance. (Faulkner, 1974)

Finally, the effective perceived noise level is represented by

$$EPNL[dB] = 10log_{10}\left(\sum\left(10^{\frac{L_{PN}}{10}}\right)\right) \quad \textbf{(2-32)}$$

This formula only works if the noise sources are located in the same place.

Additionally, other authors developed some expressions for hover (Refer to appendix F)

2.4.2 Noise generated by Engines

It is known that compressor, turbine and jet nozzle generates all the noise. Thus, to determine perceived noise level is necessary to know some geometrical and thermal qualities depending on the engine.

However, Davidson and Hargest (1965) present an empirical formula taking into account the shaft horsepower and disc loading to determine perceived noise level at 500 feet on a side line

$$L_{PN_{500}} = 5 + 17.7log_{10}\left(W\sqrt{DL}\right) \quad \textbf{(2-33)}$$

2.4.3 Total Noise Generated

To find the whole noise generated from a defined distance measure from the tilt rotor on a side line is by summing all the noise levels generated. (Johnson, 2011)

$$EPNL[dB] = 10log_{10}\left(10^{\frac{Rotor1\ L_{PN}}{10}} + 10^{\frac{Rotor2\ L_{PN}}{10}} + 10^{\frac{Engine1\ L_{PN}}{10}} + 10^{\frac{Engine2\ L_{PN}}{10}}\right) \quad \textbf{(2-34)}$$

3 METHODOLOGY

3.1 Tilt Rotor mission performance

The mission performance model is developed in order to assess the fuel burned quantity throughout a mission, theoretically flown.

To find the fuel burned it is necessary to establish a mission profile as shown in Figure 3-1 as a base line.

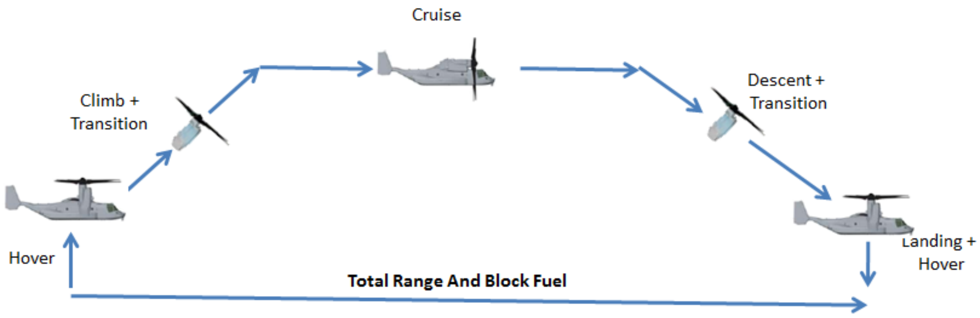

Figure 3-1 Civil Mission Profile

Then, each segment is assessed looking for fuel burned starting in warm up that depends on engines running time and throttle position; that time goes from two to five minutes at normal.

Continuing with each segment, new weights will appear at the end of each flight segment, and through making a comparison between initial gross weight and final mission weight it will be possible to find the total fuel used.

All the parameters used as inputs to simulate different cases during a mission are configuration and operational data such as flight speed, flight altitude, range required and time required depending on the mission segment as shown on Appendix A.

The tilt rotor mission performance model is built based on different modules in which each of them represents segments flown; a schematic representation about tilt rotor performance model is shown in Figure 3-2.

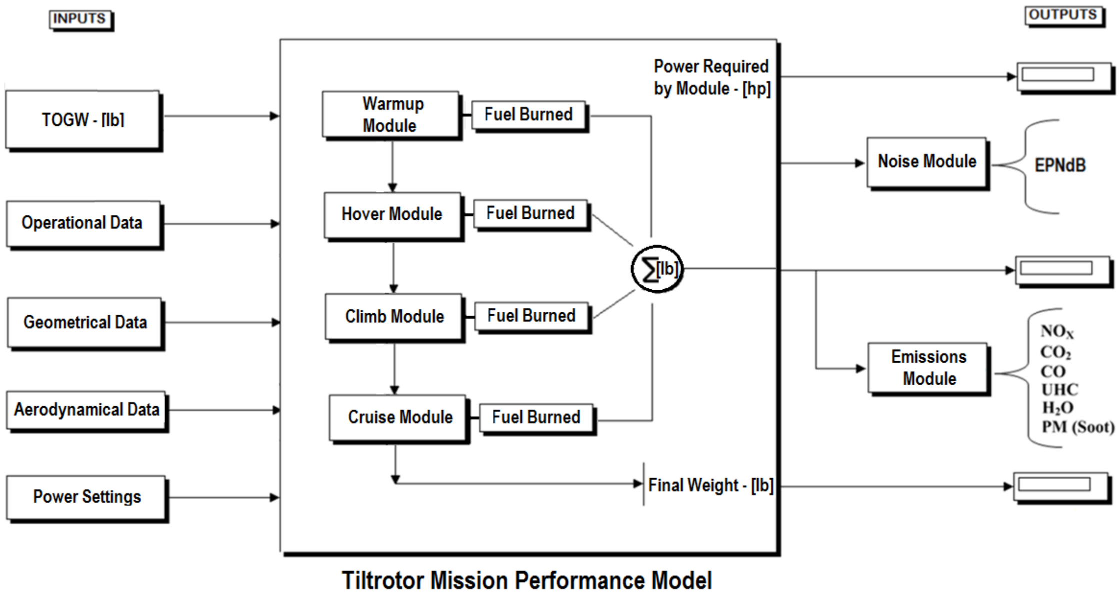

Figure 3-2 General Scheme Tilt rotor performance model

Each module is based on power required calculations depending on flight conditions, such as airplane mode (cruise and climb), helicopter mode (Hover, Climb, forward flight) and conversion flight.

Each module generates a fuel burned which will be computed in an additional module called Emissions Module to determine the amount of pollutant emissions that are released into the air.

The main outputs from the tilt rotor performance model are power required and fuel burned given by each module, final weight after complete the mission, finally, Noise given during hover state.

In this case, all modules are arranged to evaluate a corporative mission which is the base line to perform the study.

3.1.1 Engine Performance

Modelling of engine performance is required to be integrated in each module in order to get the appropriate value of fuel consumption during each segment.

There are different ways to include engine characteristics into tilt rotor performance model starting with evaluate or simulate engines using different computational tools such GasTurb 11 commercially available or TURBOMATCH developed by Cranfield University.

Those tools are good enough the run different performance conditions from design-point up to off-design point getting some outputs such sfc, fuel flow, and power available depending on different rating conditions. Also, with these values could be possible build some equations and add them on the mission performance model.

Another alternative is obtaining all engine performance characteristics and build some blocks provided by Simulink called Lookup tables and insert them on each module in order to evaluate and get fuel burned.

For this project lookup tables was the option chosen to insert engine parameters into the model because those tables are able to interpolate and extrapolate depending on the inputs used to find the correct value.

Engine performance characteristics and fuel flow conditions for airplane mode and helicopter mode are shown in appendix B which corresponds to the engine Pratt and Whitney PT6C-40 installed in Model 300 tilt rotor. (Bell Helicopter Company, 1969)

3.1.2 Warm-up and Hover Module

Warm-up module is the first step to start the performance study that is included on the tilt rotor performance model. For the operation nature at this point, few inputs are required to use this module as standalone such (i.e. Time, Throttle position and ambient conditions) in addition, power available and fuel flow data given by engine is included as shown in Figure 3-3, also, the only output given by this module is fuel burned which is subtracted to the weight input used in the next module called Hover Module as shown in Figure 3-4.

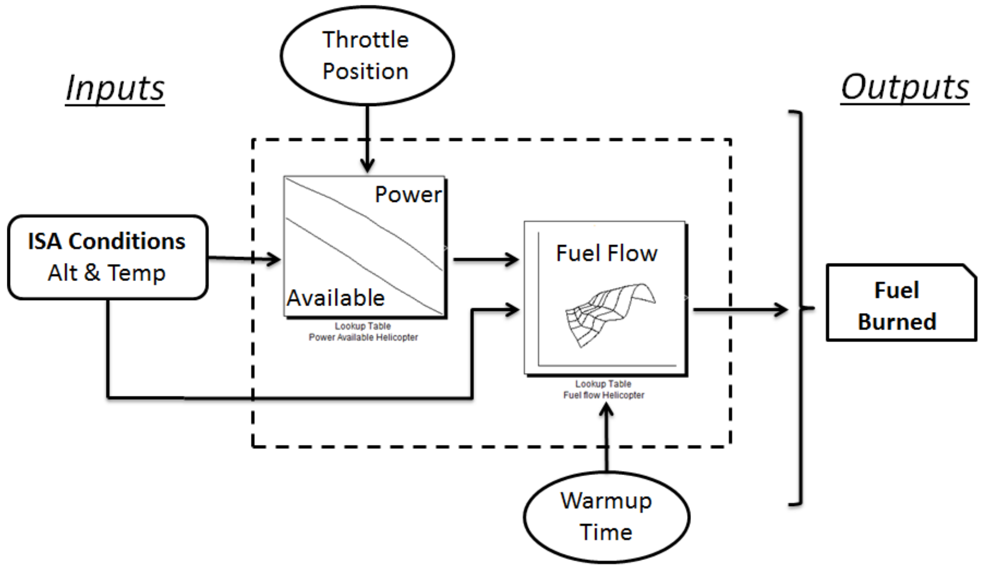

Figure 3-3 WarmUp Module Scheme

Hover Module is more complex because it needs more data including geometric, aerodynamic, Weight, operational and powerplant inputs. Those inputs are necessary to run some subroutines such induced, profile and parasite power required which together generate total power required.

That total power is used as input along with time and altitude into fuel flow lookup table in order to get fuel burned as shown in Figure 3-4.

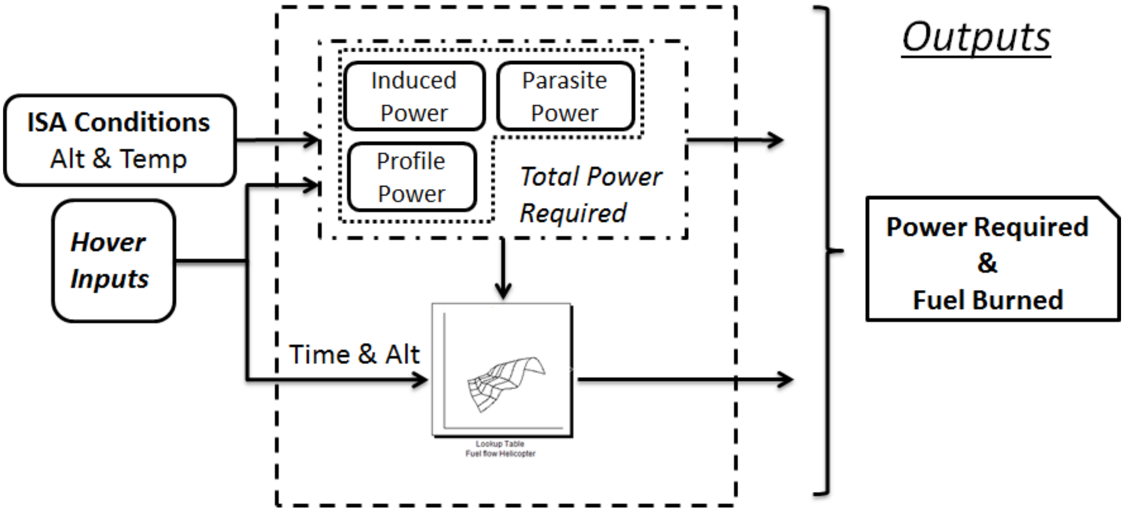

Figure 3-4 Hover Module Scheme

Additionally, Hover module works to landing segment because is driven by the same equations but varying the weight used.

3.1.3 Conversion/Climb Module

The following module works similar as hover module. However, it contains an additional subroutine called climb power required shown in Figure 3-5 in order to get the total power required at different forward and vertical speeds. Additionally, this module are able to measure power requires at different nacelle angles.

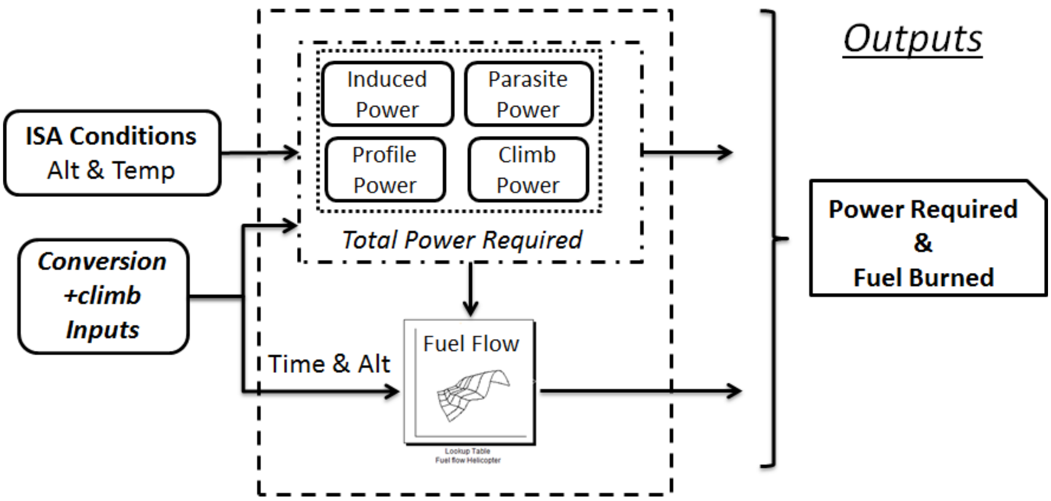

Figure 3-5 Conversion/Climb Module Scheme

Also, it is necessary to clarify that input as geometric, aerodynamic and so on are needed to each module.

3.1.4 Climb and Cruise Modules

Since the tilt rotor has the versatility to flight or operate as a turboprop airplane, Climb module is needed to determine power requirements. However, the subroutines are different because the equations used represent a turboprop airplane performance that is why parasite power does not show.

This module works with the principle of exceed power which is necessary to determine climb speed and power required. In Figure 3-6 are shown block such power available which is used along with Total power required to get exceed power.

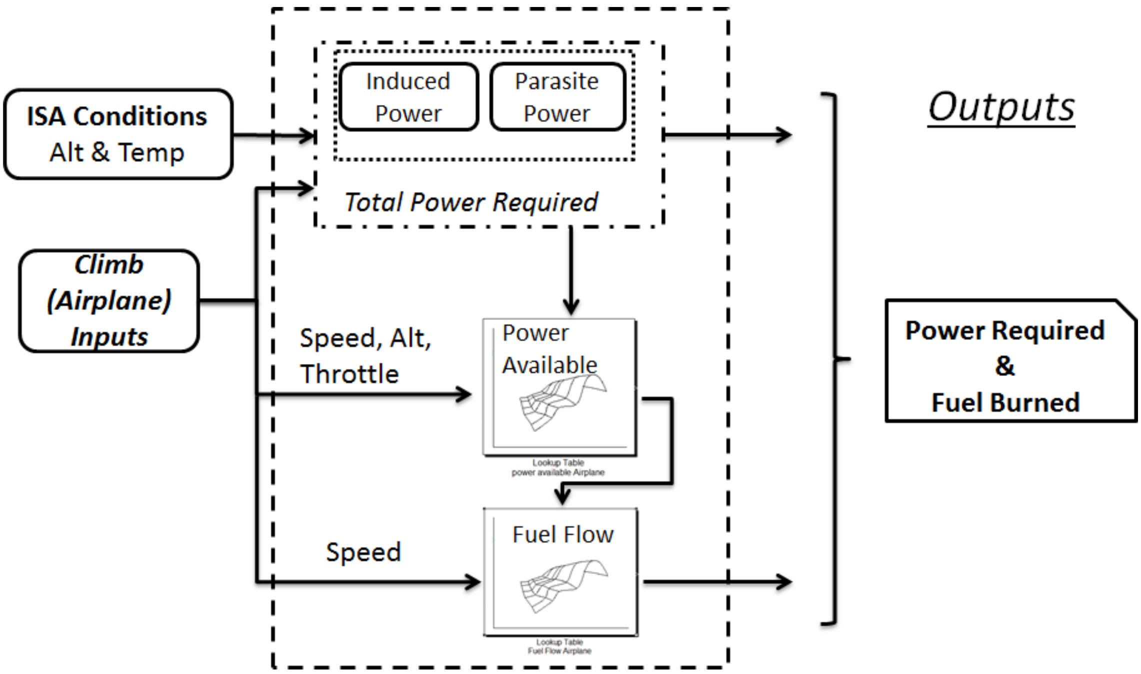

Figure 3-6 Climb Module Scheme

Some inputs for this module are final segment altitude, throttle position and forward speed including the previous known.

Cruise Module works base on Airplane performance theory where range is one input along with other in order to determine the fuel used on the biggest segment of the mission.

In Figure 3-7 some operational input are cruise speed, range required and altitude.

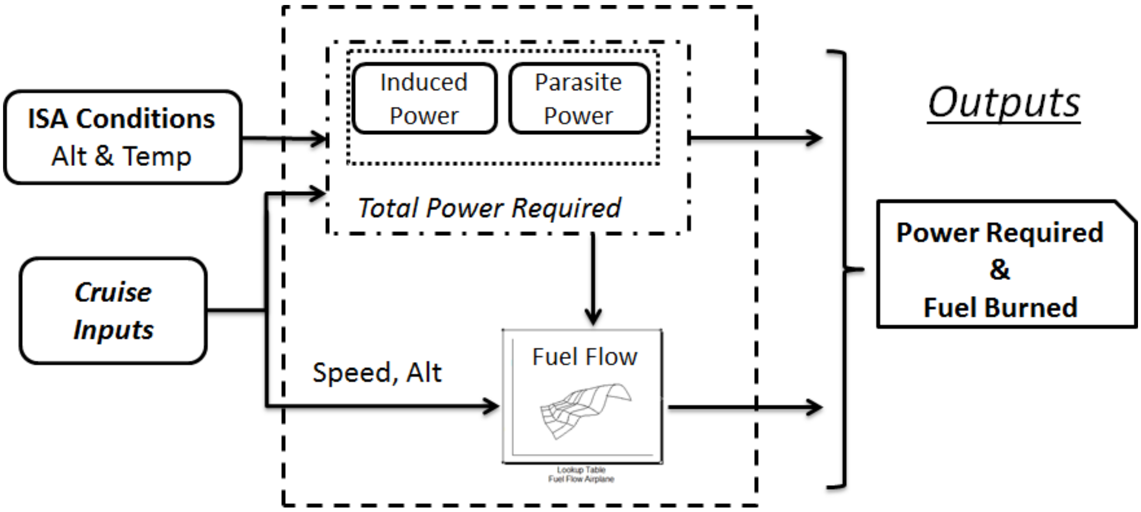

Figure 3-7 Cruise Module Scheme

3.1.5 Pollutant Emissions and Noise Modules

Since the aim of this project is to measure the emission released into the air, Pollutant emission modules was built taking into account all the fuel burned by each segment as well as power requirements and fuel .

This module is driven by the equation previously shown in chapter 2 regarding to emissions. Also, Noise module was assembled at hover modules in order to measure Noise levels around airfields which affect the population directly. Additionally, Noise module was determined by equations which work mainly in hover state because for the remaining segments such cruise or climb equations needed are very complex and for dynamic state.

3.2 Verification of Capabilities

To be sure that all the obtained values are proper, hand calculation were done in Excel spreadsheet to get and compare power requirements, also, additional calculations were made in order to determine performance capabilities as show in table 3-1.

Table 3-1 Performance Capabilities Verification for Model 300 at 9500 lb. SL Conditions

Helicopter Mode	**Units**	**Model 300 Data**	**Simulation Data**	**Deviation %**
Hovering Ceiling, OGE	ft	11600	12000	-3.33
Maximum Speed	Knots	134	137	-2.18
Maximum Rate of Climb	ft/min	3480	3497.53	-0.50

Airplane Mode	**Units**	**Model 300 Data**	**Simulation Data**	**Deviation %**
Maximum Speed @TO power	Knots	311	313	-0.32
Maximum Rate of Climb	ft/min	3750	4293.29	-12.65
Service Ceiling	ft	26200	25900	1.15
Range@10000[ft]	nm	522	524.6	-.0.49

It is necessary to keep in mind that a percentage of errors exist; in this particular case the deviation obtained was up to $\pm$13% on the worst scenario because lack of information is presented and some assumptions made.

Assumptions as:

- Constant prop-rotor efficiency
- Constant Rotor blade chord.
- Average blade drag coefficient was assumed similar as a helicopter rotor equivalent to 0.016 (Leishman, 2006)

Additional graphs were made using equation from chapter 2 in order to determine and check the correct tendency of the curves to get important capabilities points such as maximum rate of climb of 3497 ft/min on helicopter that happen at 65 knots Figure C-2, service ceiling equal to 12000 ft figure C-3, maximum speeds in airplane mode at SL equal to 290 knots and 313 knots at 10000 ft shown in figure C-4, among other. (Refer to Appendix C)

3.3 Design of Evaluation Technique

In order to obtain the minimum fuel burned and also pollutant emissions, a parameter study for single-variable took place during the mission proposed in which air traffic constraints were not taking into account called free flight.

Every test or study were performed on each segment looking at what flight condition is better to reduce the fuel required on each segment and by this mean assess the total emissions during the mission performed.

It is imperative to clarify that all the possible variations of any variable are limited to the tilt rotor performance such maximum speed, service ceiling or rate of climb. Also, each evaluation performed was made in sequence making variations and combinations on each segment or module.

4 RESULTS AND DISCUSSION

The following chapter shows results using the tilt rotor mission performance model during a mission profile theoretically flown. Variations regarding to speeds, power settings, rates of climb and time were taking into account in order to evaluate the mission proposed.

Additionally, through this kind of variations, it was possible to identify the operational way to reduced fuel needed and its implications regarding to pollutant emissions.

4.1 Mission Profile Considerations

For this study the mission proposed (i.e. Corporative) was suggested choosing two Heliports in the United Kingdom. Also, this mission was performed at one way starting at the Point A (Glasgow Heliport) to point B (London Heliport) as shown in Figure 4-1.

Figure 4-1 Tilt Rotor corporative mission Profile

For this mission some operational assumptions were established in order to accomplish it as a base line:

1. Warm Up and time to wait take off clearance 5 min
2. Hover/Take off at 50 ft for 4 min with 1600 lb of fuel, crew, passengers and baggage representing TOGW 9500 lb.
3. Conversion / climb reaching 1500 ft.
4. Climb Airplane at 110 knots TAS reaching cruise altitude of 10000 ft.
5. Cruise at 180 knots TAS to the drop off point flying 302 nm
6. Descent at final point gliding
7. Hover/Landing at 65 ft for 4 min

The graphical representation for departure path is shown Figure 4-2.

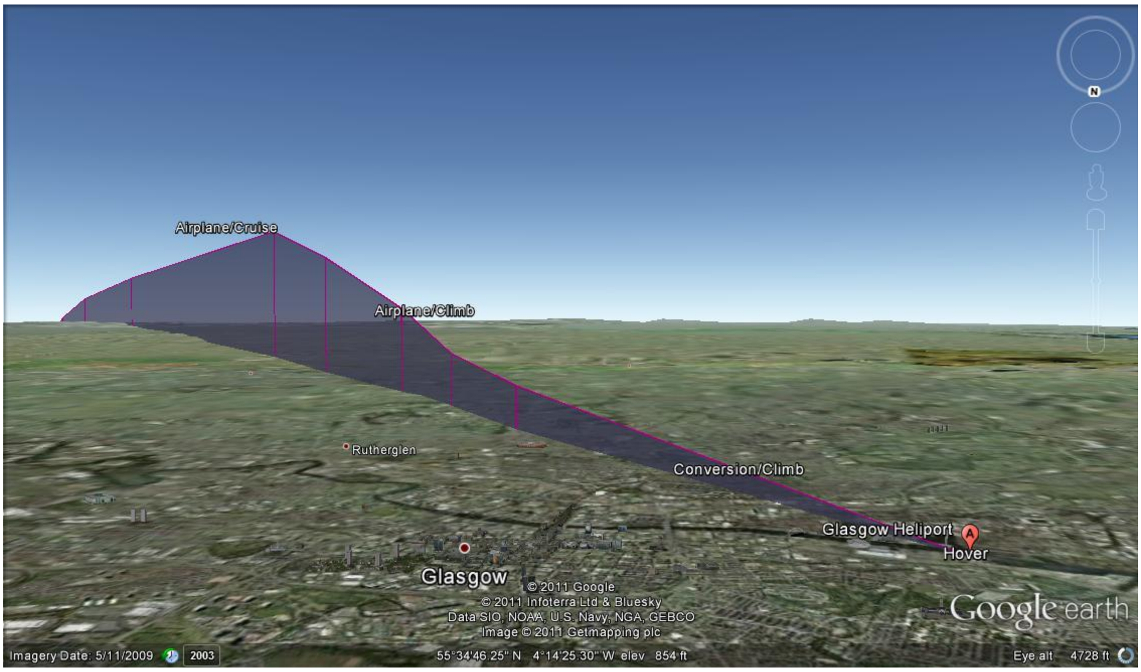

Figure 4-2 Departure path to reach cruise altitude

4.2 Parametric Study

In order to perform the parametric study different variables or inputs were changed looking at the impact on the emissions produced by each segment throughout the mission.

For the single variable studies Table 4-1 shows the input variation throughout the mission.

Table 4-1 Input Variation per Flight Phase

FLIGHT PHASE	INPUT VARIATION
Warm Up	Warm Up time [min]
	Power setting [%]
Hover / Take off	Hover time [min]
	Altitude [ft]
Conversion / Climb	Forward speed [knots]
	Climb speed [ft/min]
	Nacelle Angle [deg]
Airplane Climb	Forward Speed [knots]
	Power setting [%]
Cruise	Forward Speed [knots]
Hover / Landing	Hover time [min]
	Altitude [ft]

Different combinations were made for this study in the order of 70 run cases combining different inputs.

4.2.1 Warm Up Phase

Different variations were taking into account at this mission stage changing time and power settings in order to get the effect on the fuel burned and its emissions during this phase and for the entire mission.

Looking at the single segment making variations over the time along with power setting it is appreciable to see the fuel burned going up during engine power setting increment as shown in Figure 4-3.

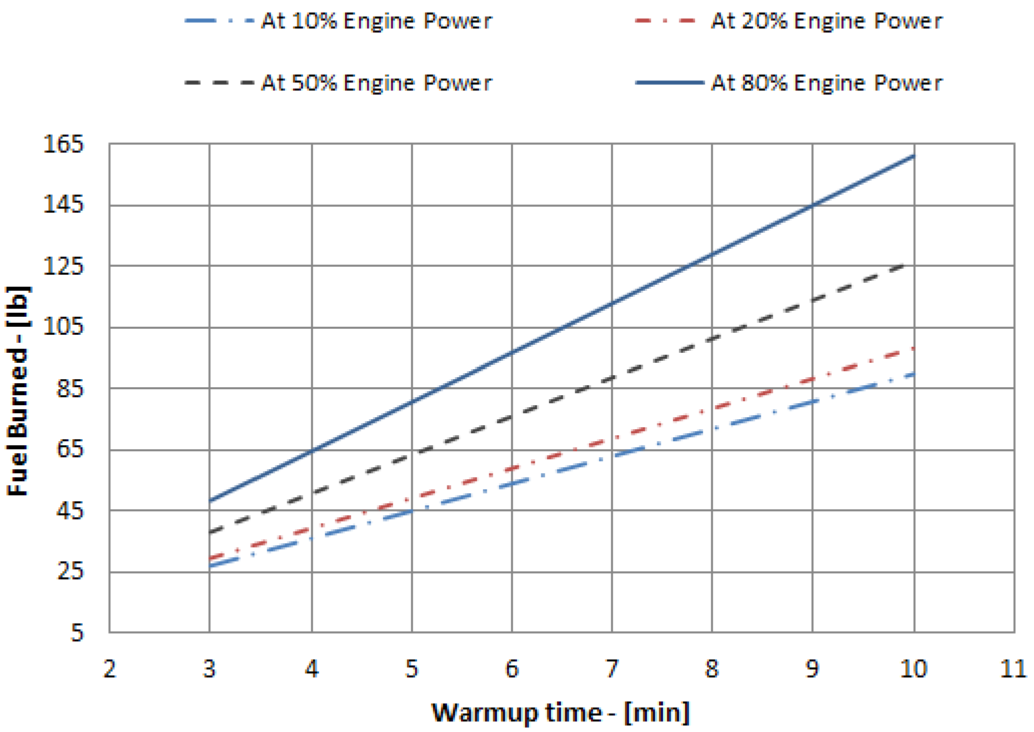

Figure 4-3 Fuel burned variation at different times and different power settings.

However, at the moment to intend getting a reduction of fuel burned, some pollutant emissions vary reverse, Some emissions increase their values enormously at low power setting such as CO and UHC due to lack of oxygen required to form CO_2 and H_2O, that is the reason of CO_2 and H_2O levels are very low.

In the operational procedure it is not recommended spend more than 5 min warming up if it is desired to save operational fuel.

On the other hand, NOx and PM emissions are low at low power settings due to low temperatures at the combustion chamber getting high at more power required as shown in figure 4-4.

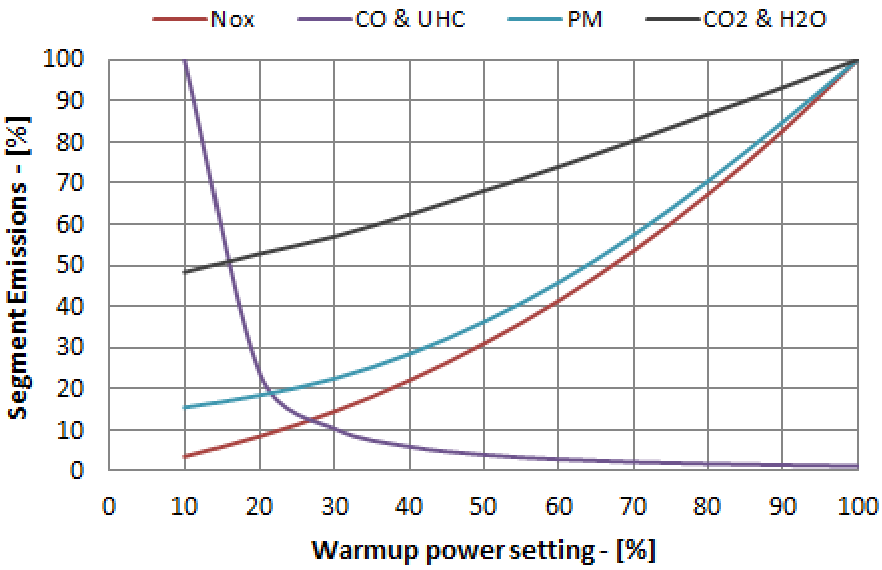

Figure 4-4 Segment Emissions at different power settings

Now, having a general point of view, if the time during warm up is reduced 2 min, mission fuel burned has a reduction up to 2% as shown on figure 4-5.

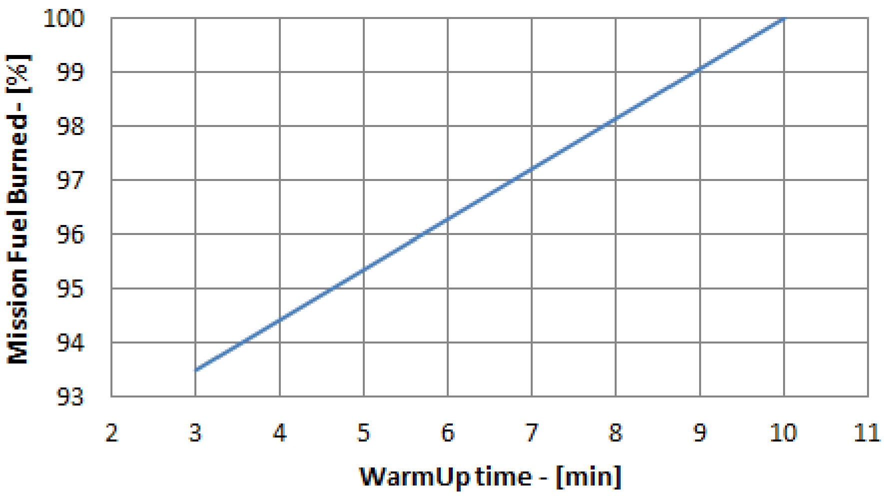

Figure 4-5 Mission fuel burned at different time with 50% power setting.

Also, it is evident a reduction of about 1.4% of NOx and PM, 1.8% of CO_2 and H_2O, and 3.4% of CO and UHC at the missions end as shown in figure 4-6.

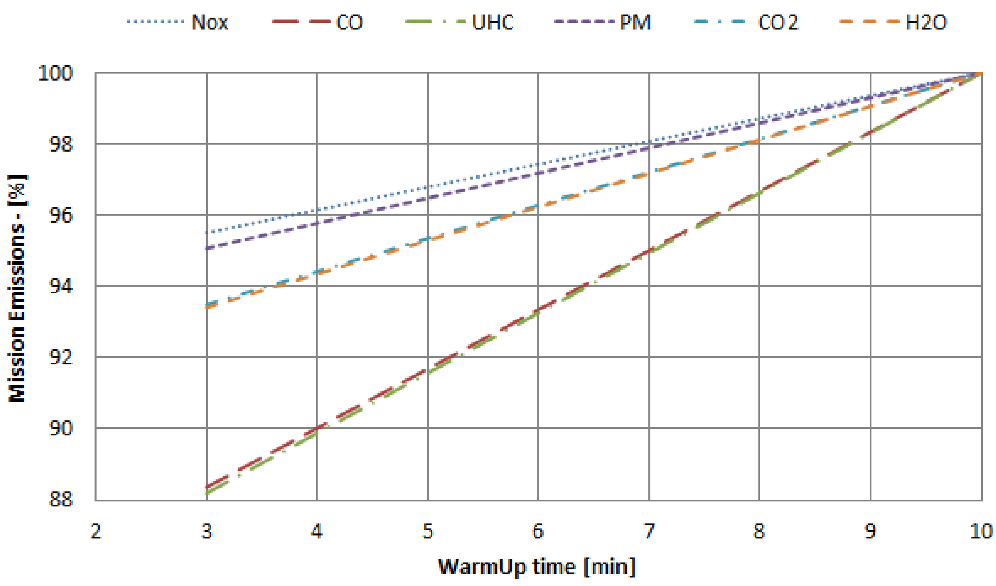

Figure 4-6 Mission Emissions at different time with 50% power setting

However, as any rotorcraft during warm up is running its engines in idle, this power setting represents 10% of throttle positions, getting less fuel burned and a large amount of CO being this pollutant emission very toxic.

4.2.2 Hover / Take Off Phase

In order to analyse hover phase, variation in hover altitude and time were made.

Those variables are controllable by the pilot during the tilt rotor operation. Thus, making a variation during the hover time from 4 min to 2 min a representative reduction up to 2% of mission fuel used is achievable as shown in figure 4-7.

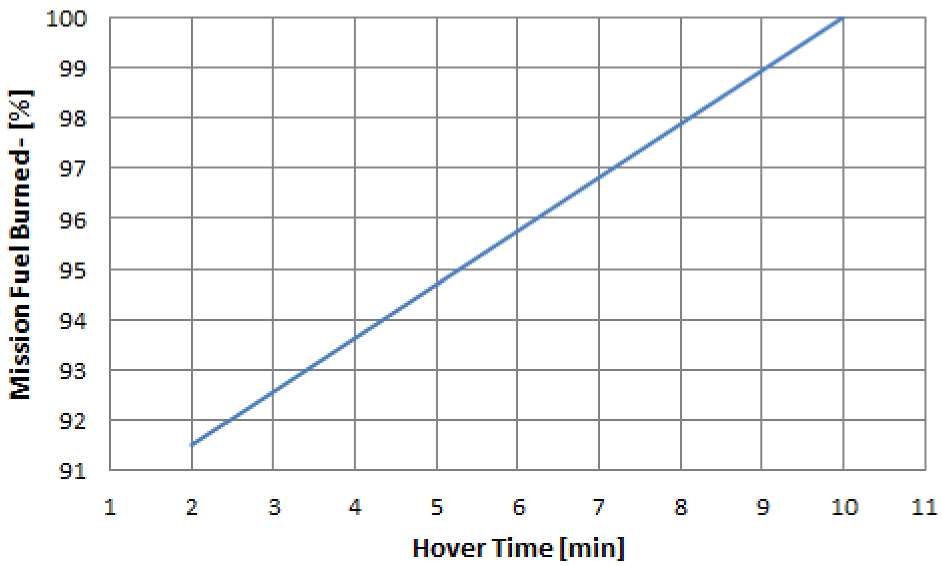

Figure 4-7 Mission fuel burned with different hover time at 50ft

At the moment to achieve 2% reduction of fuel burned, it was possible to obtain a significant reduction over mission pollutant emissions, having a decrement of around 2.7% of NOx and PM, 3.1% of CO_2 and H_2O, 3.9% of CO and UHC. As shown in figure 4-8.

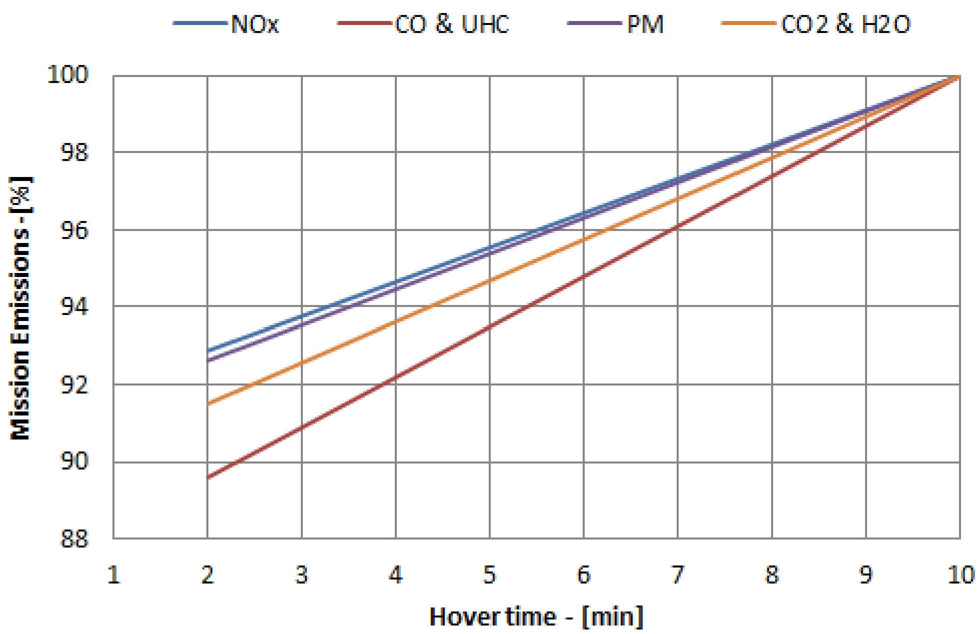

Figure 4-8 Mission Emissions with different Hover times at 50ft

On the other hand, making variations regarding hover altitude and taking into account the ground effect it is getting an increment of fuel burned while the altitude is increasing as well. That is due to the increment of power needed at high altitudes around two times the rotor diameter as shown in figure 4-9.

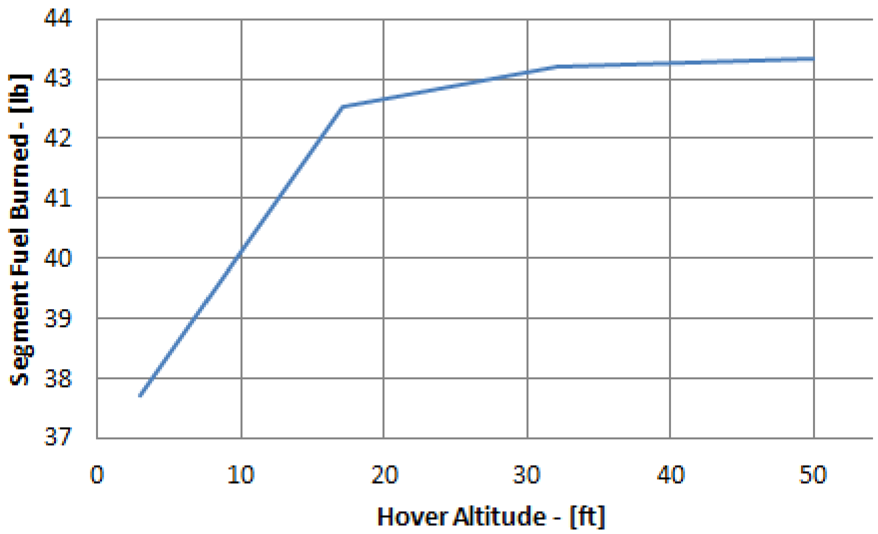

Figure 4-9 Segment fuel burned at different hover altitude during 3 min

Since the power needed varies while the altitude varies as well, segment emissions have a similar trend depending on the emissions to be evaluated.

Emissions such NOx, PM and CO_2 & H_2O are directly proportional to fuel burned. However, CO and UHC have the opposite behaviour due to the enough oxygen to become in CO_2 and H_2O as shown in figure 4-10.

For the operation during this phase, it is recommended to achieve a balance for hover altitude and emission due to fuel burned. In this case around 10 ft it is possible to obtain a fuel reduction of 7%.

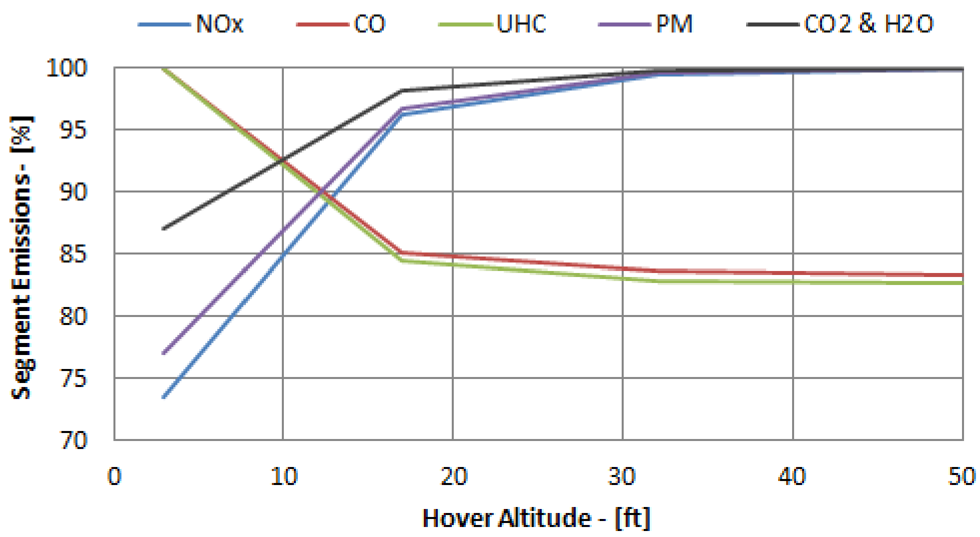

Figure 4-10 Segment Emissions at different hover altitude

Unfortunately, this reduction of pollutant emission is not as high as desired because this segment has a very short effect during the whole mission in terms of altitude change.

4.2.3 Conversion / Climb Phase

Since the tilt rotor has the versatility to turn itself from a helicopter to an airplane, this study evaluated the fuel burned and its correlated emissions during different nacelle angles, rate of climb and forward speeds during six steps, each of them equivalent to 250 ft from SL to 1500 ft altitude.

During each step a nacelle angle was chosen, recreating a conversion corridor from helicopter mode to airplane mode.

However, it is necessary to keep in mind that the entire variation made is limited by the rotorcraft performance capabilities.

For the first climb step with nacelle angle equal to 80 deg at different rate of climb from SL to 250 ft shows a fuel reduction while the rate of climb increases. Also, this reduction goes up to 45% as shown in figure 4-11.

The total fuel burned during this stage is reduced if the rate of climb increases, while more rate of climb more fuel flow is required but the time required to reach any particular altitude is less, thus, fuel burned is less.

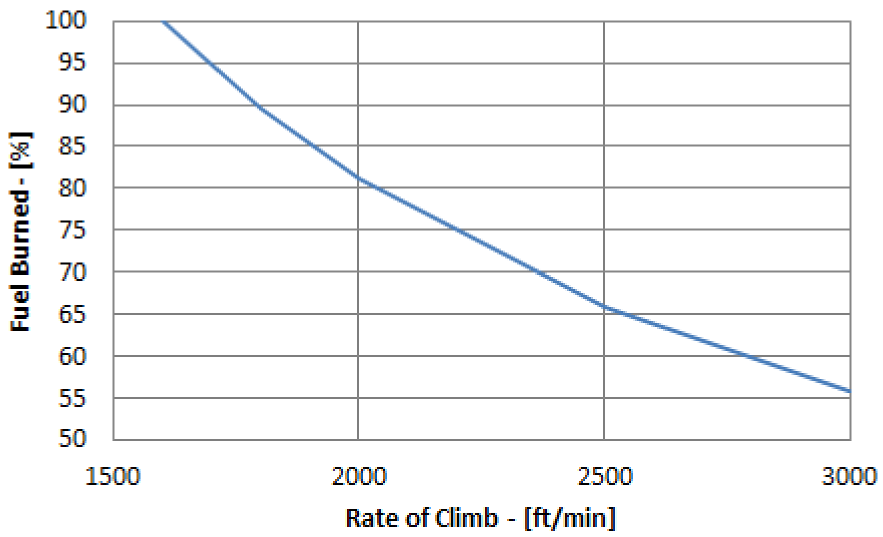

Figure 4-11 Variation of fuel burned at different rate of climb with 80 deg nacelle angle

This reduction of fuel brings a reduction of around 41% of NOx and PM, 49% of CO and UHC, 44% of CO_2 and H_2O as shown in figure 4-12.

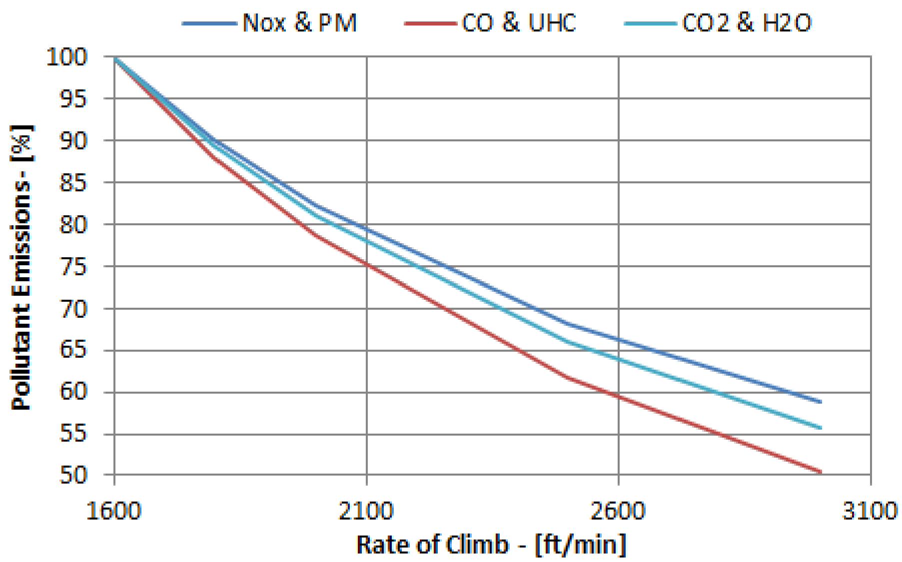

Figure 4-12 Variation of pollutant emissions at different rate of climb with 80 deg nacelle angle

For all variation angles during the climb phase reaching 1500 ft of altitude it is recommended to ascent with the rate of climb as close as possible to the maximum allowed which give low fuel burned and pollutant emissions as well.

4.2.4 Climb Phase

From this point, the tilt rotor is in airplane mode and the variations made are over power setting and forward speed.

As a normal procedure the power setting for this phase was 85% and keeps the same speed during climb while cruise altitude is reached.

In figure 4-13 the variation of fuel used during climb phase is higher during 75% power setting because fuel flow is less but time required to reach cruise altitude is more.

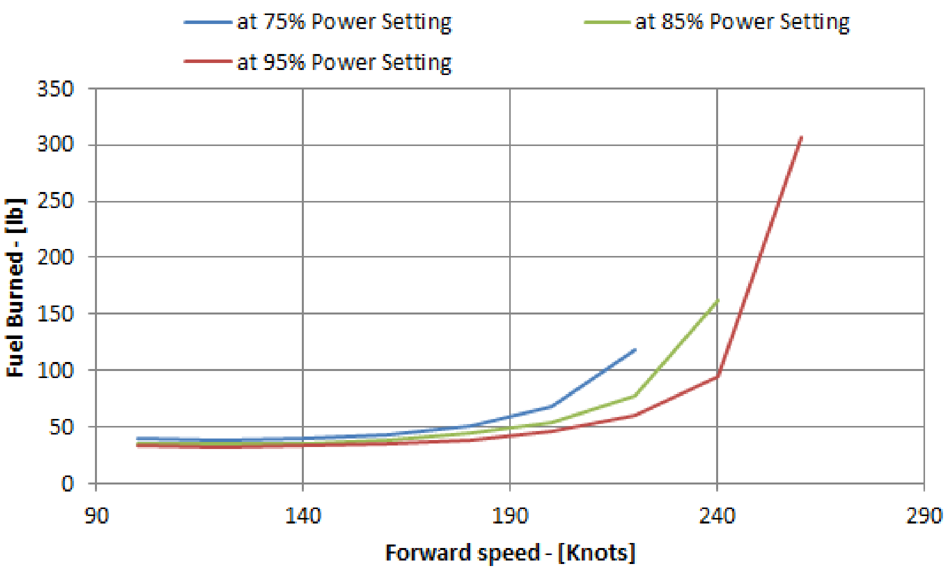

Figure 4-13 Fuel Burned Vs Forward speed at different power setting

On a global view, there is a small reduction of emission if the forward speed used goes from 120 up to 150 knots the total reduction is up to 0.7% on CO & UHC.as shown in figure 4-14.

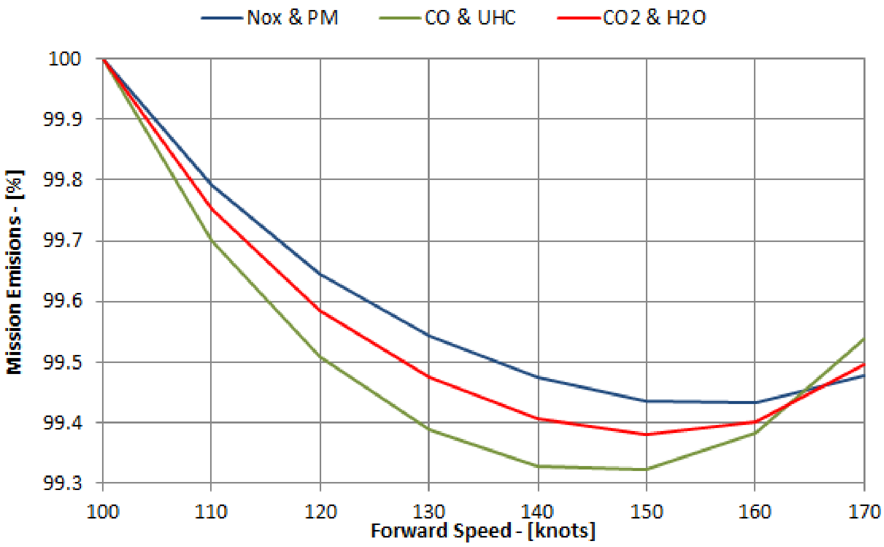

Figure 4-14 Mission emission Vs forward speed at 85% power rating

In climb conditions, it is recommended used 85% of power because there is enough power, in other words, excess power to overcome any problem during the flight.

4.2.5 Cruise Phase

Since cruise is the largest mission segment, the variable used to measure emissions and fuel burned was cruise speed. Unfortunately, altitude variations over 10000 ft were not considered for two reasons: no pressurized cabin and lack of engine information above this altitude.

While cruise speed is changing power requirements are changing as well turning higher at more speed. However, the tilt rotor should fly to maximize range as close as possible to minimum drag speed, in this particular case between 180 and 200 knots as shown in figure 4-15.

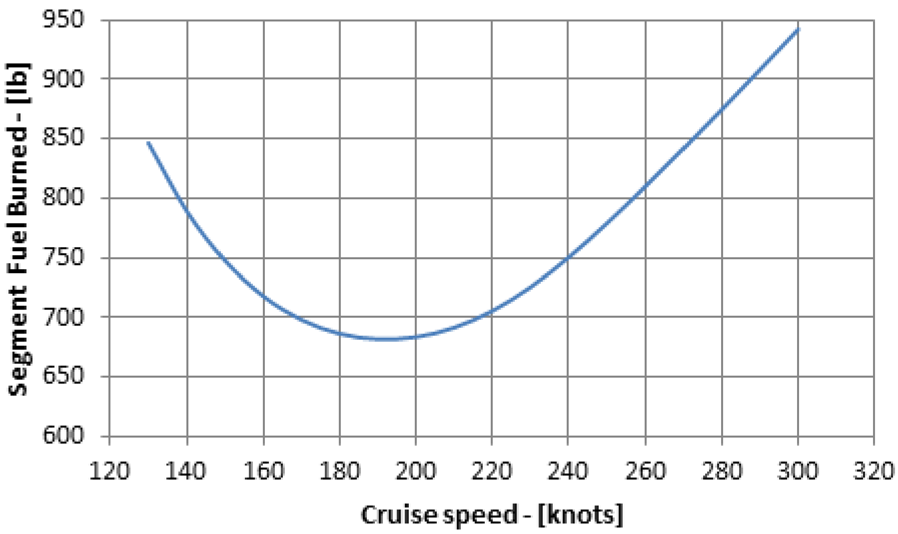

Figure 4-15 Cruise Fuel Burned due to cruise speed at 10000ft

Therefore, this behaviour brings some benefits regarding to emissions in figure 4-16, getting important reductions of about 50% of CO and UHC, 25% of CO_2 and H_2O. On the other hand, there is an increment of PM and NOx between 53% and 60%.

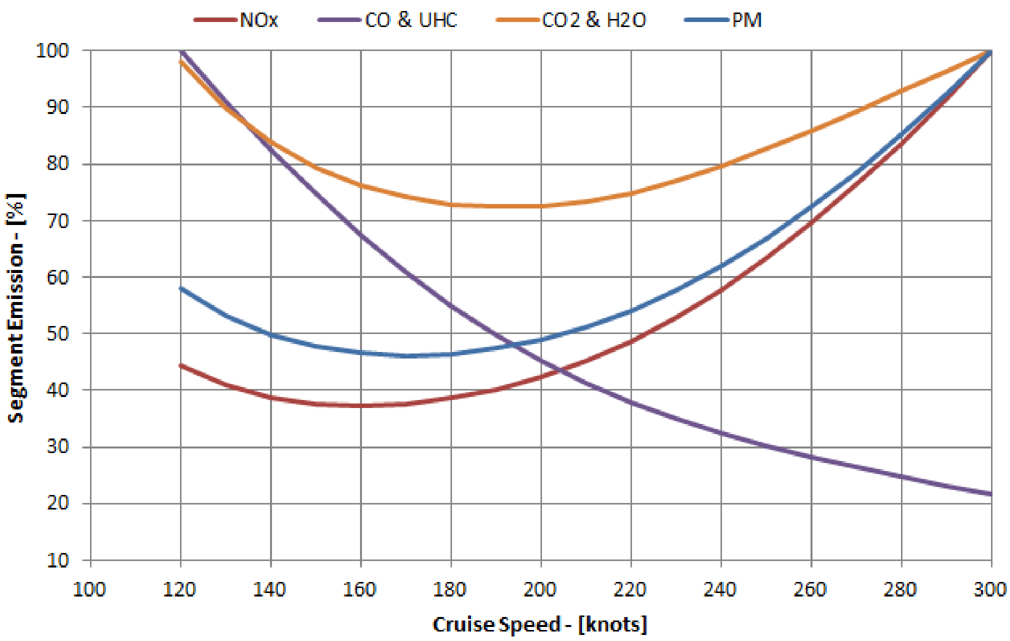

Figure 4-16 Cruise segment emissions at different cruise speed

It is important to clarify as cruise is the longest part of the mission; these reductions of pollutant emissions have a positive impact. Thus, a good recommendation is performing this segment as close as possible to the maximum range speed in order to reduce fuel, emissions and time.

4.2.6 Hover / Landing Phase

For hover at the end of the mission, the trend for fuel burned and emissions are the same compare to hover / take off. However, the amount of fuel used and emission in landing are less than take off because the tilt rotor's weight is less. Thus, power requirements are less too.

Figure 4-17 shows the reduction of fuel burned making a comparison between hover take-off and landing having a considerable reduction of about 6.5%. Additionally, this brings emission benefits regarding to NOx, PM, CO_2 and H_2O reduction of around (13% NOx, 11%PM, 6% CO_2 & H_2O). On the other hand, Increments on CO and UHC in the order of 7% are presented as sown in figure 4-18.

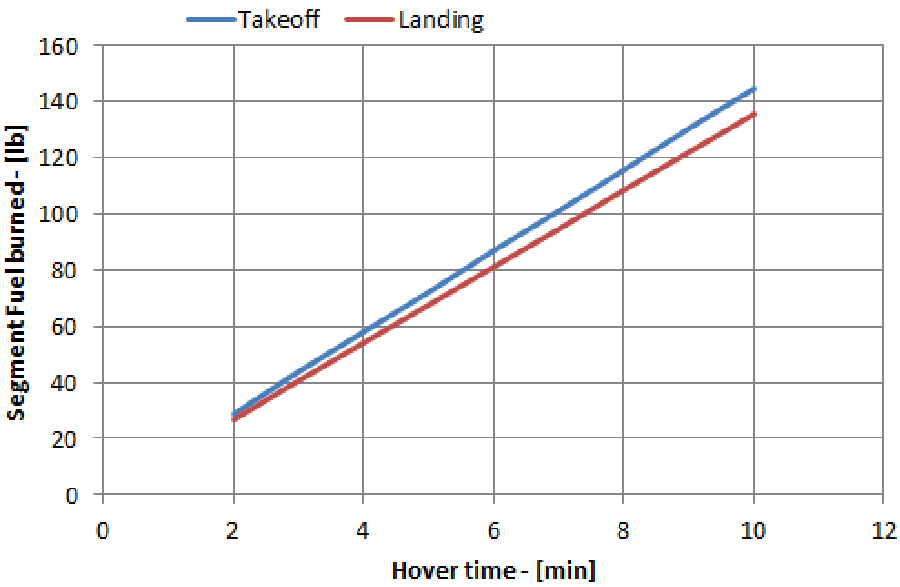

Figure 4-17 Variation of fuel burned at different hover time.

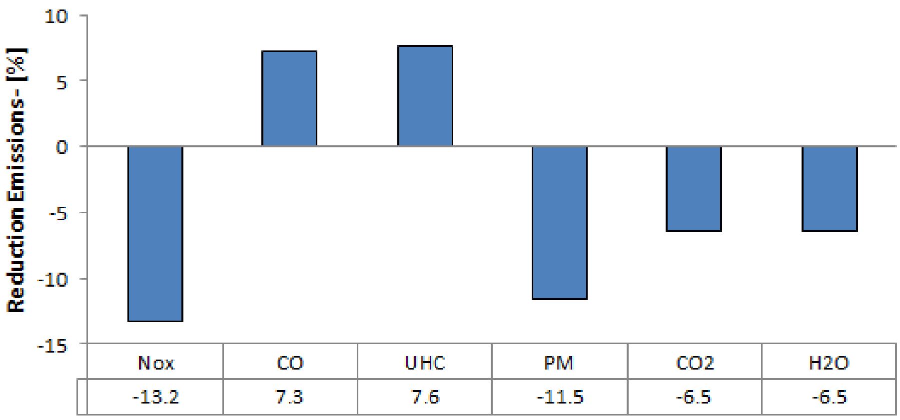

Figure 4-18 Emissions Reduction between Hover / Take-off and Landing

4.2.7 Turboprop Aircraft and Helicopter

Performing a comparison between a turboprop aircraft and helicopters with similar weight, range, and service altitudes and flying the same distance, it was found that it is a significant increment in terms of fuel burned compared with an aircraft, However, It is most likely use a tilt rotor in order to replace a helicopter to perform the same mission as shown in table 4-2.

Table 4-2 Comparison of Emissions turboprop aircraft and helicopter

	Cessna Caravan 208	***BE200***	***Helicopter Bell 412***	***Sikorsky s76B***	***Model 300***
Fuel Burned	192.48 kg	278.509 kg	1217.25 kg	673.38 kg	386.01 kg
CO_2	608.23 kg	880.08 kg	3846.51 kg	2127.88 kg	1219.76 kg
NOx	1.10 kg	1.2 kg	13.81 kg	5.54 kg	1.91 kg
CO	881.36 g	6.42 kg	2.85 kg	2.94 kg	4.207 kg
UHC	46.9 g	1.13 kg	2.38 kg	2.34 kg	5.32 kg

In order to save fuel during a long range flight, it is not convenient using a tilt rotor to replace a turboprop; additionally, the technology involved, in this case in engines are the key factor in terms of pollutant emissions.

In the other hand, it is worth to use a tilt rotor to perform long missions from difficult access areas to other because it saves time, less pollutant emissions and fuel burned instead of helicopter.

To measure fuel burned and emissions for aircraft it was used a data base provided by Aviation and Environment (FOI 2001, accessed Nov 2011) and data base for helicopters from (FOCA, 2009)

4.2.8 Noise in Hover

For this tilt rotor the maximum Effective perceived noise level evaluated from 500 ft side lined was 91 EPNdB. This result is good enough comparing to the real value in the order of 90 EPNdB.

Also, additional evaluations were made changing the observer distance up to 3000 ft, getting a considerable reduction on the perceived noise as shown in figure 4-19.

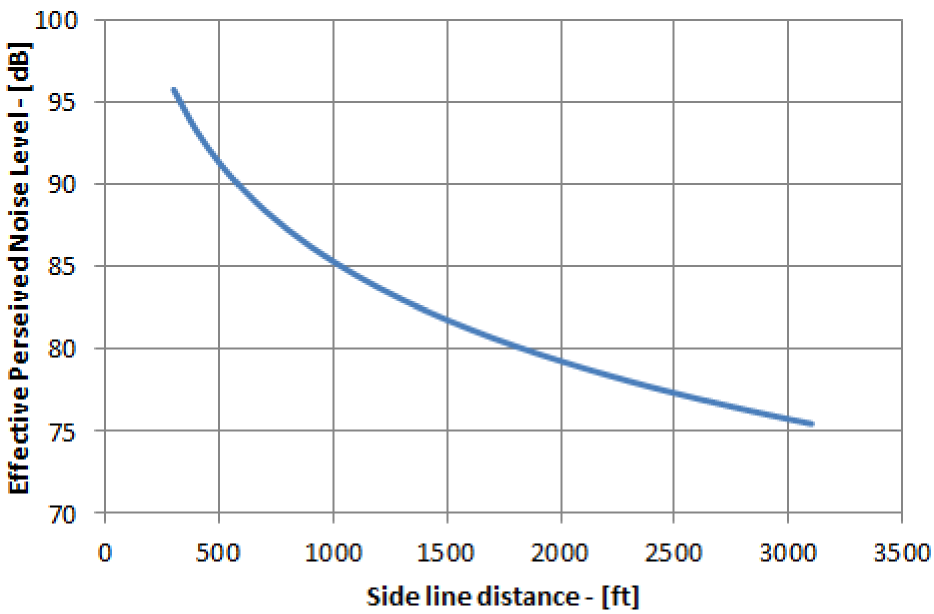

Figure 4-19 Calculated Noise level at different distances

Additionally, it was possible to evaluate hover noise on the landing phase having the same behaviour with less generated noise. The reason, less power required at the mission ends producing less engine noise. Thus, a reduction of total noise around 3% was obtained.

This noise is not a big problem near to the busiest airport areas, because community residences are far enough to avoid it. However, small heliports near to suburban areas are more affected by the noise, because low ambient noise is presented and communities are exposed.

As shown in table 4-3 in terms of noise, turboprop aircraft are more likely to be used instead of helicopters and this particular tilt rotor.

Table 4-3 Aircraft and Helicopter noise levels

	Cessna Caravan 208	***BE200***	***Helicopter Bell 412***	***Model 300***
EPNLdB	64 dB	66 dB	92 dB	91 dB

Information regarding aircraft noise was found in FAA advisory circular (AC-36-3H) and for Bell 412 (Bell Helicopter, 2001)

4.2.9 Error

The tilt rotor mission performance model was assessed in order to have coherent results with the inputs used. However, changing the value of $\overline{C_{do}}$ Blade drag coefficient in the order of 2%, the result in power required will change drastically, in the order of 8%. It means that this value must be very accurate at the moment to run any simulation.

5 CONCLUSION

A tilt rotor mission performance tool was developed in order to calculate power requirements for each part of the mission profile proposed, as well as fuel burned which provides enough outputs to be used in other modules such as Emissions Module.

A Noise Module was developed in order to evaluate the noise generated in hover segments, suggesting that this particular tilt rotor generates the same perceived noise levels as compared with some current helicopters and it is noisier than turboprop aircraft.

An evaluation of emissions was made on each segment of the mission profile, making variations on inputs where the pilot is in control, obtaining different results which provide some operational recommendations in order to reduce fuel and some emissions such CO_2 and H_2O.

It is recommended to spend as minimum a time as possible about 3 min in the warm-up in order to reduce the production of CO, making hover at 10 ft altitude in order to have less fuel burned due to ground effect, as the same time production of emission are almost at minimum.

It was found that performing climb looking for the maximum excess power is possible to save time while is reaching cruise altitude. Also, total fuel burned is reduced.

To reduce the fuel burned in cruise in the mission proposed it is recommended flying at maximum range speed, production of CO_2 and H_2O is reduced. However, if it is desired to reduce NOx and PM it would be necessary to fly near to the maximum endurance speed.

A comparison between turboprop aircraft, helicopter and the tilt rotor was made with the same distance flown, it was found that the fuel burned and levels of CO_2 are higher using tilt rotor rather than turboprop aircraft. On the other hand this is much better than helicopters.

The tilt rotor mission performance tool has the capability to assess different components, such as engines, if the information is available. Also, the evaluation of other tilt rotors can be performed.

All the results provided by the simulation tool are accurate enough in spite of the assumptions made about the prop rotor efficiency and Blade drag coefficient.

6 RECOMMENDATIONS FOR FUTURE WORK

Since the tilt rotor mission performance model was developed to evaluate a single mission in steady state mode, it would be recommendable improve the tool to assess different missions in unsteady state or dynamic looking at the advantages that Simulink possess.

In spite of noise module is working properly in hover statically, it would be recommendable build an additional module to assess a dynamic mission in order to get some results throughout the time.

It is suggested assemble the tilt rotor mission performance model into a multidisciplinary framework in order to assess different systems and its implication regarding power requirements and fuel consumptions.

The results of pollutant emission provided by the tilt rotor performance model would be useful to be use by an environmentalist.

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APPENDICES

Appendix A. Breakdown of Inputs and Outputs Tilt rotor mission performance model

Table A-1 Inputs and Outputs Tilt rotor mission performance model

Category	Inputs	Outputs
Power plant Data	n - Number of Engines	
	Power Level [%]	
	η - Prop-rotor efficiency	
Operational Data	Altitude (Hover, climb)	
	Temp (each segment)	
	Time (Warm-up, Hover)	
	Climb, Forward, Cruise speed	
	R - Range	
Weight Breakdown (beginning)	Empty Weight	**Power Required**
	Crew Weight	**Fuel Burned**
	Passengers Weight	**Emissions**
	Fuel	**Noise Levels**
Geometric Data	Rotor diameter	**Final Weight**
	A_b - Rotor blade area	
	c_b - Rotor blade chord	
	σ - Rotor Solidity	
	f - Fuselage drag plate area	
	bw - Wing span	
	c - Wing Chord	
	θ - Nacelle Angle	
Aerodynamic Data	V_T - Rotor tip speed	
	$\overline{C_{do}}$ - Blade drag coefficient	
	C_L - Lift Coefficient	
	e - Oswald efficiency factor	
	C_{do} - Parasite drag coefficient	

Appendix B. Engine Performance

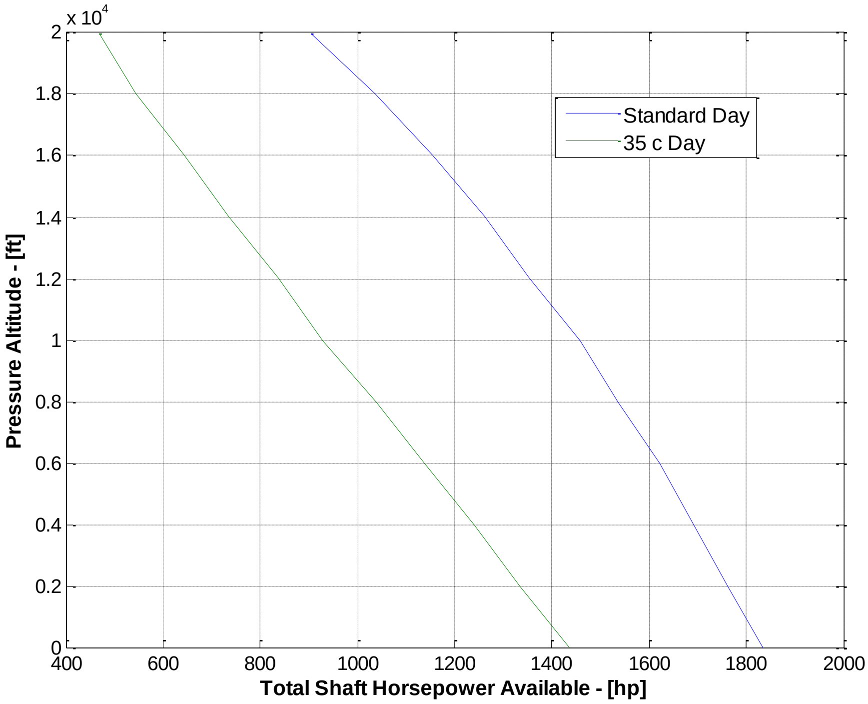

Figure B-1 Data for Power Available Helicopter Mode Normal Power

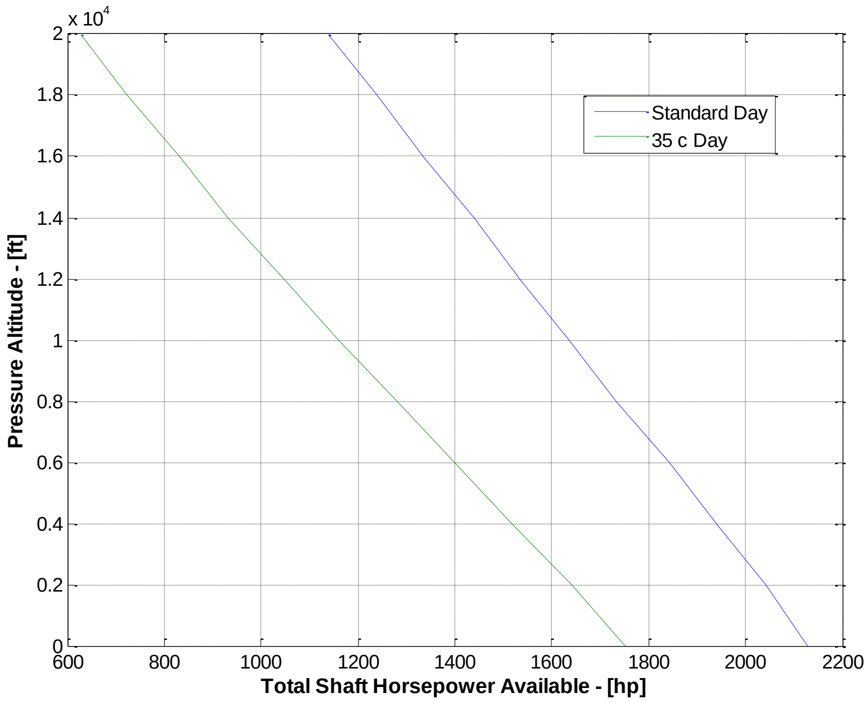

Figure B-2 Data for Power Available Helicopter Mode Take-off Power

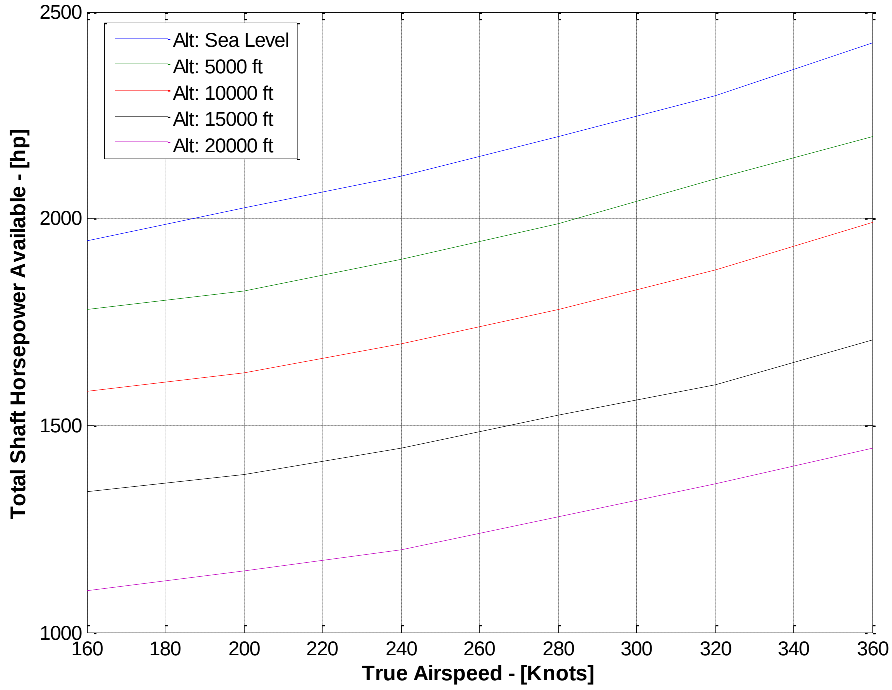

Figure B-3 Data for Power Available Airplane Mode at different Altitudes Normal Power

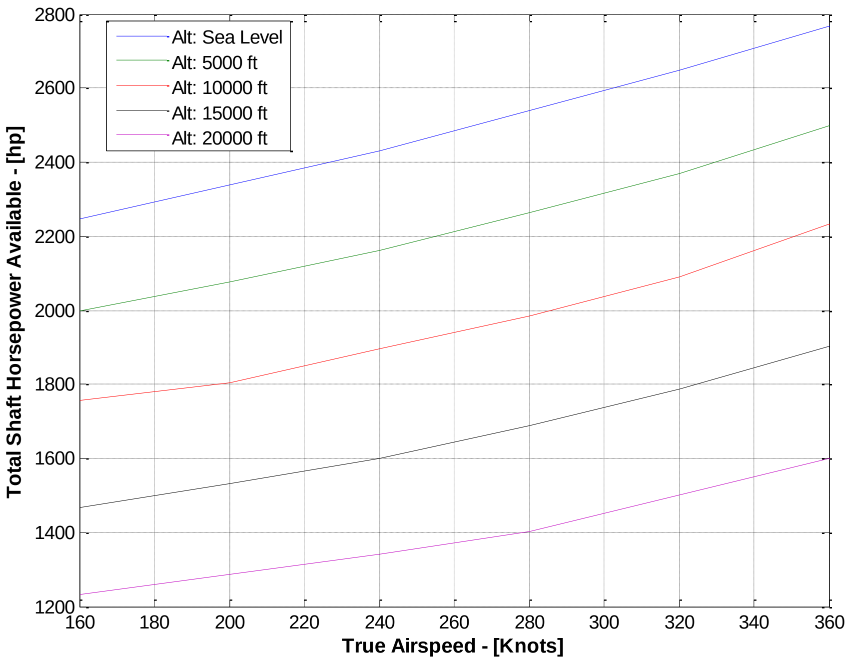

Figure B-4 Data for Power Available Airplane Mode at different Altitudes Take-off Power

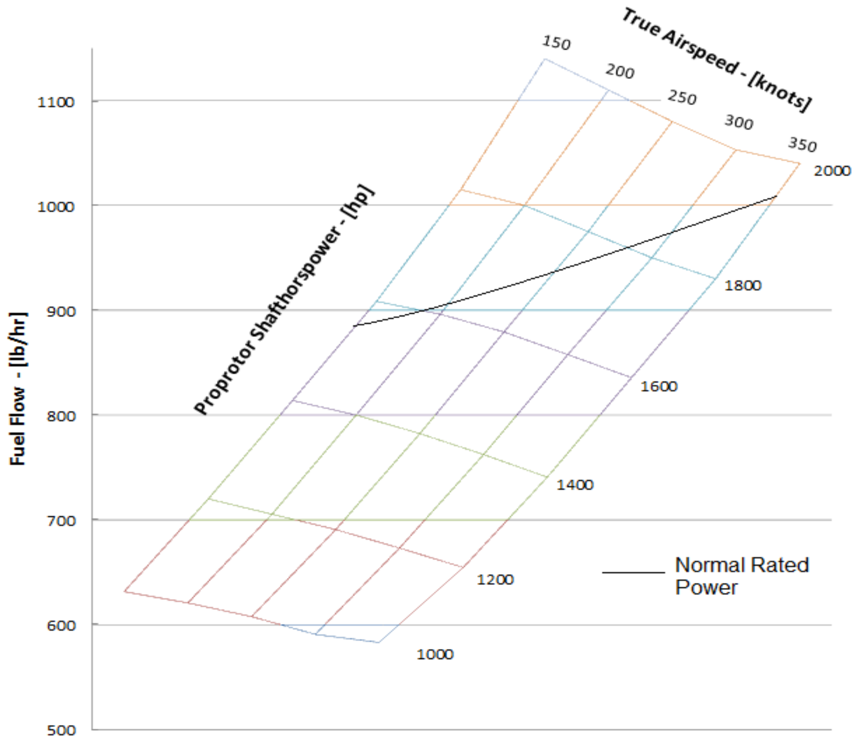

Figure B-5 Data of Fuel Flow in Airplane Mode at 10000 ft Conditions. (Bell Helicopter Company, 1969)

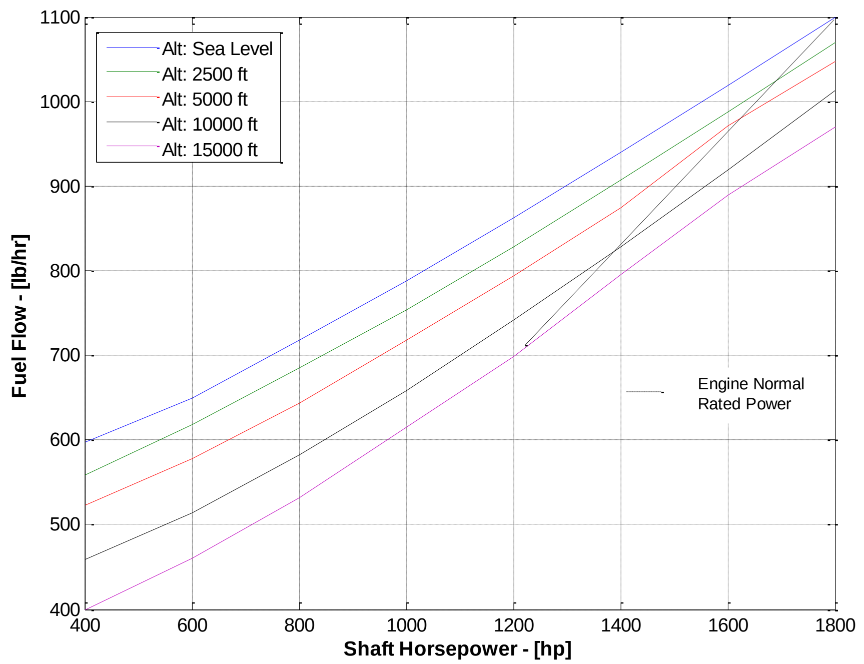

Figure B-6 Data of Fuel Flow in Helicopter Mode at different altitudes (Bell Helicopter Company, 1969)

Appendix C. Verification Performance Capabilities

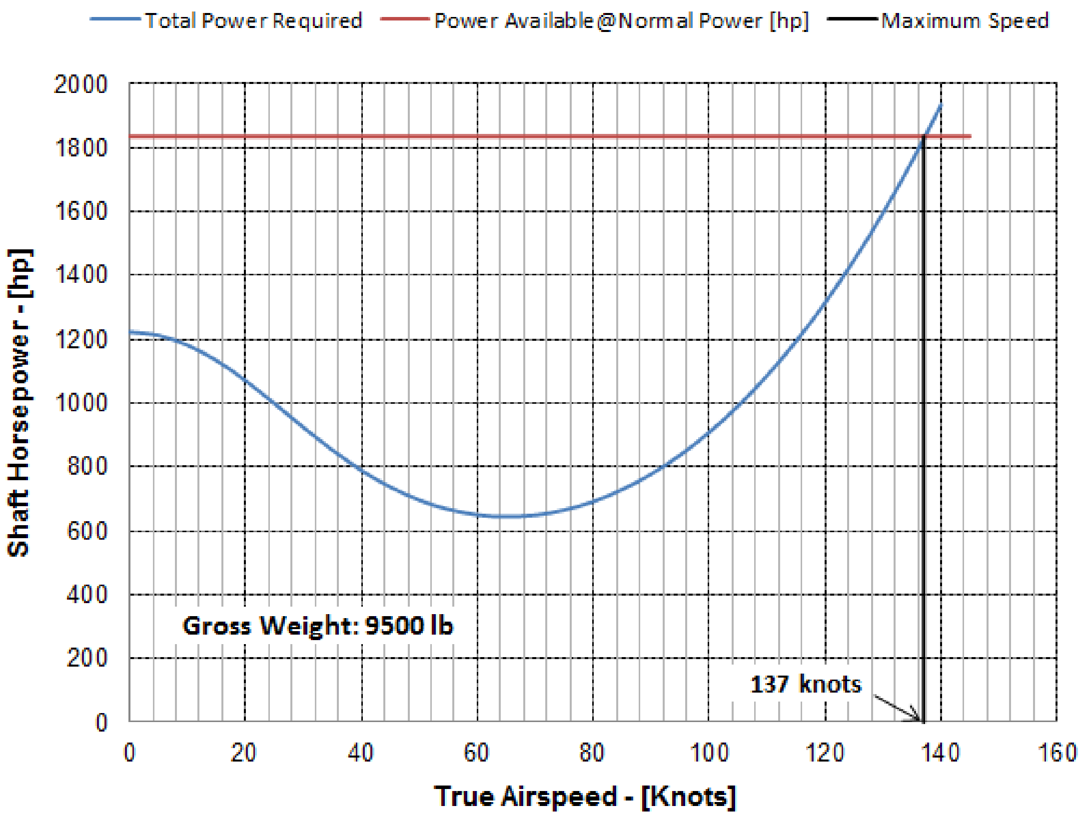

Figure C-1 Power required and power available as a function of Airspeed for Helicopter Mode at SL Conditions

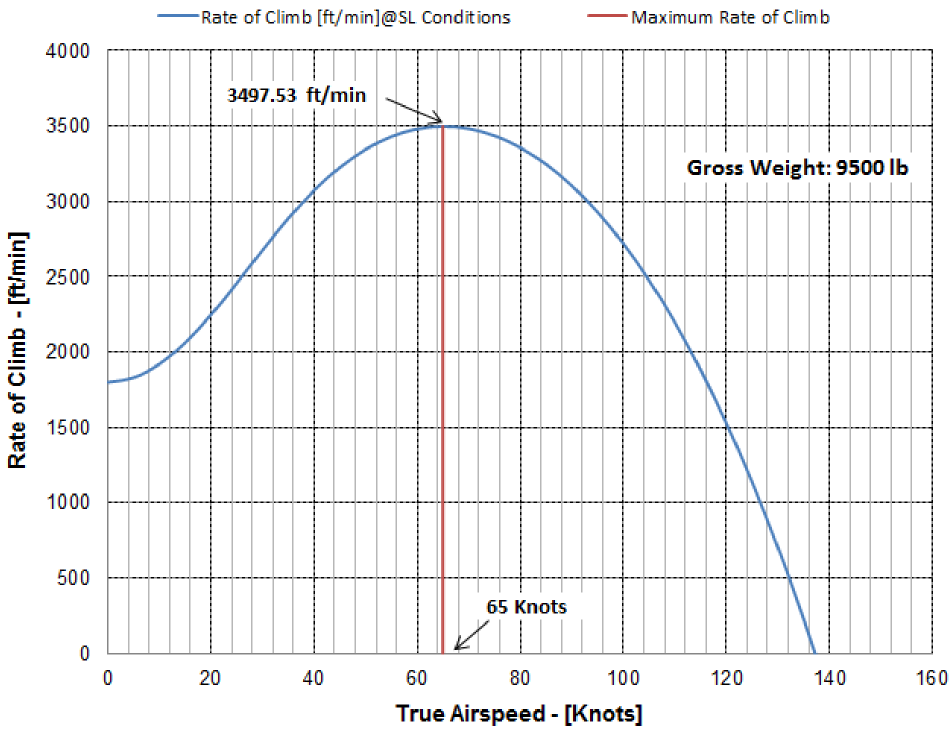

Figure C-2 Rate of Climb as a function of Airspeed for Helicopter Mode at SL Conditions

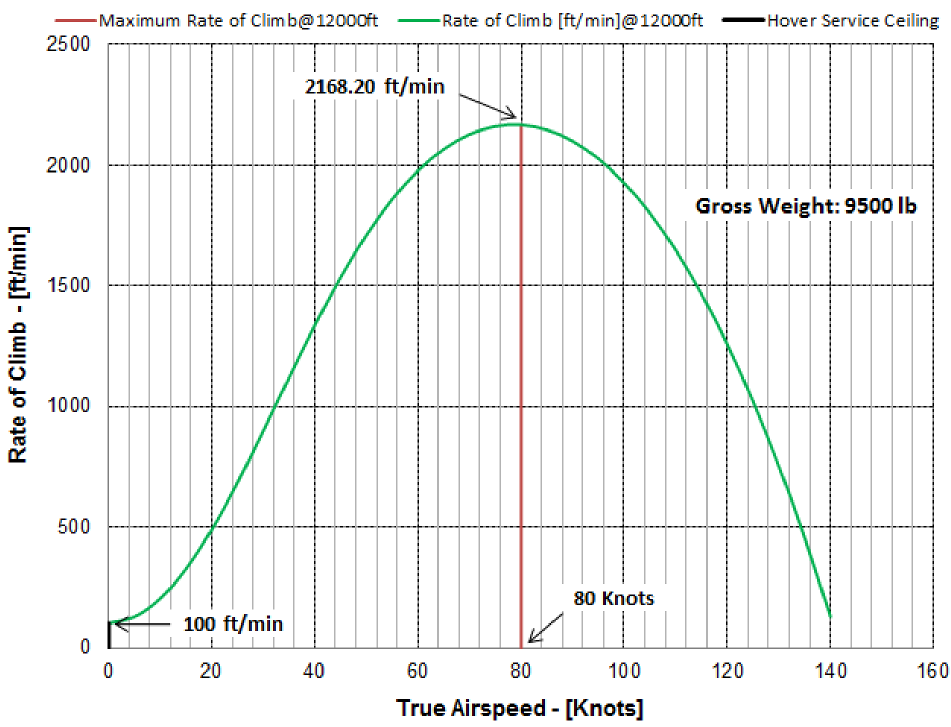

Figure C-3 Rate of Climb as a function of Airspeed and Hover service ceiling for Helicopter Mode at 12000 [ft]

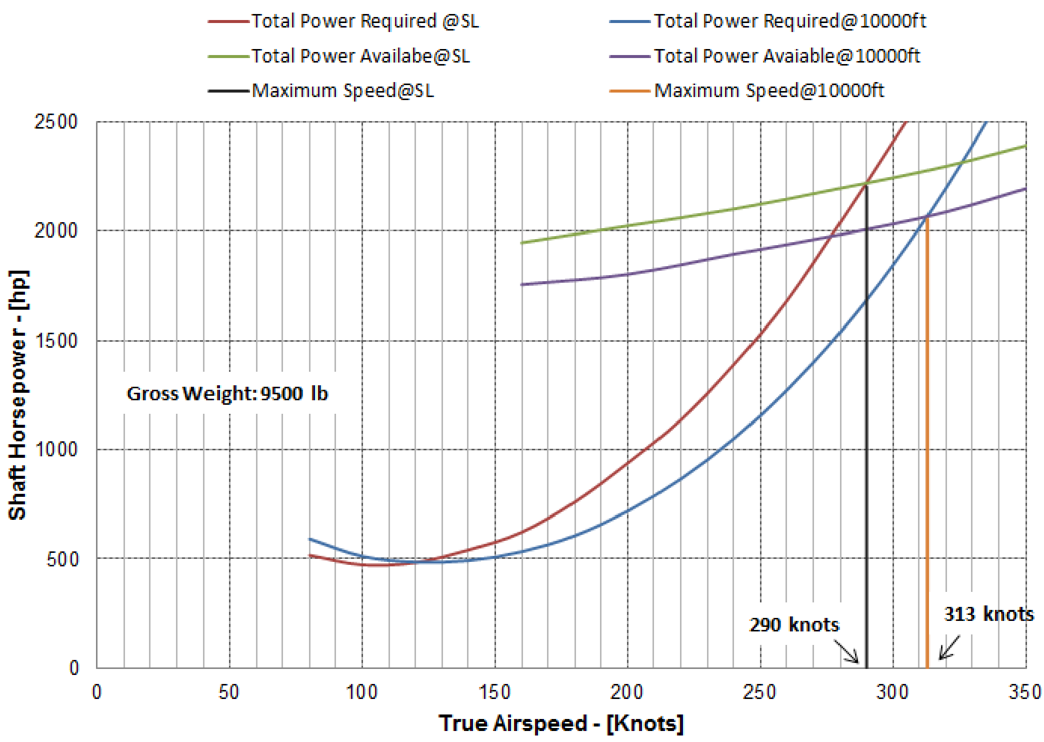

Figure C-4 Power required and power available as a function of Airspeed for Airplane Mode at SL and 10000 ft Conditions

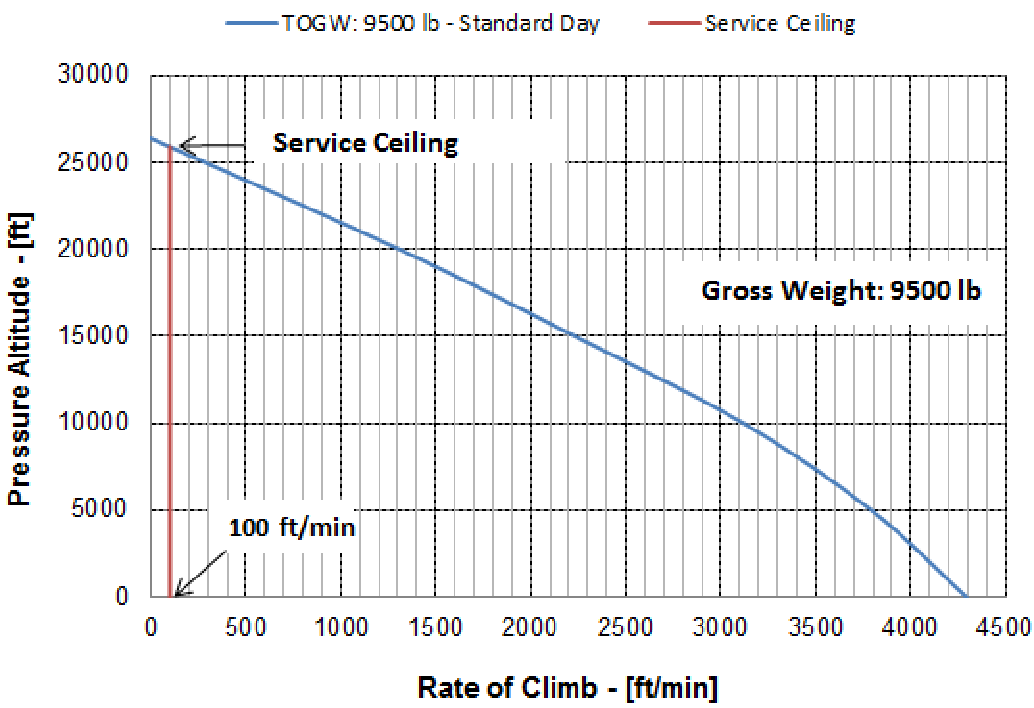

Figure C-5 Maximum Rate of Climb and Service Ceiling for Airplane Mode at SL Conditions

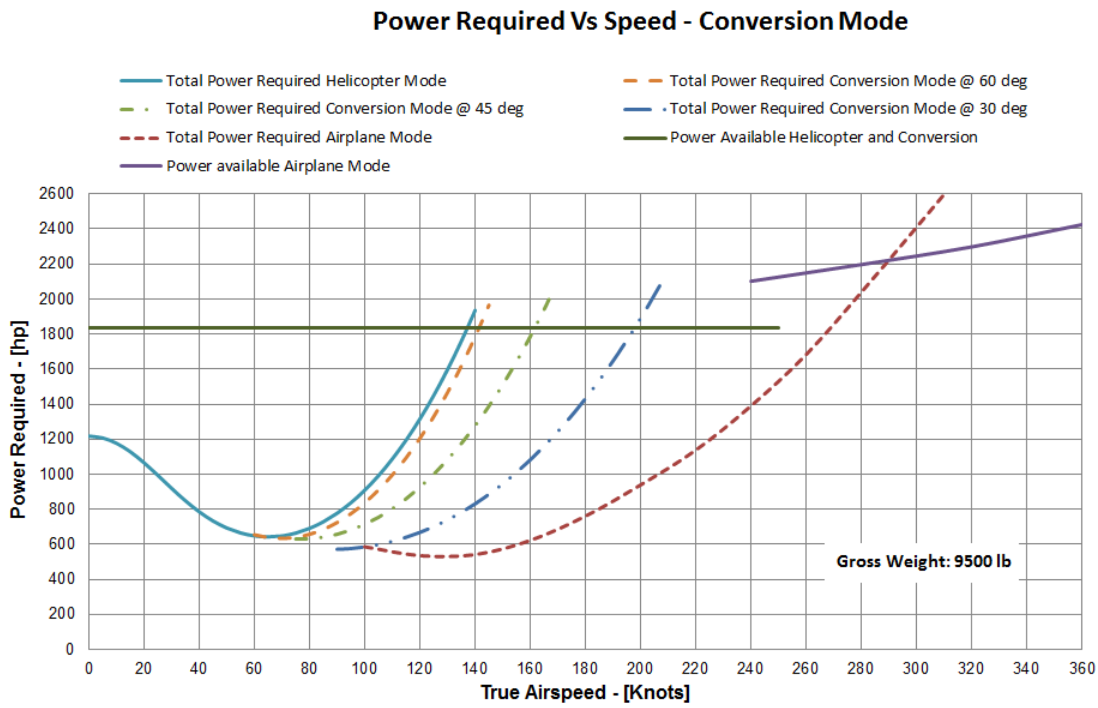

Figure C-6 Total Power required and power available as a function of airspeed for Conversion Mode at SL Conditions. Level Flight

Appendix D. Parametric Study

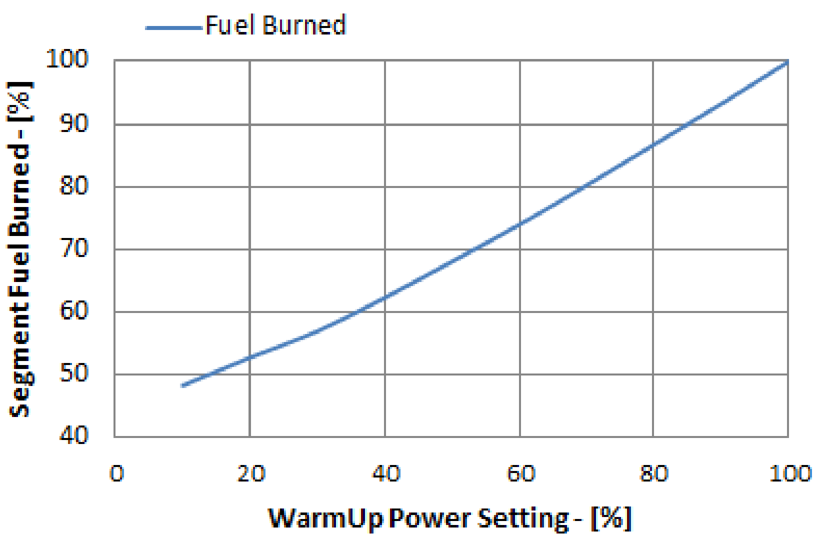

Figure D-1 Fuel Burned variation at different times and different power settings

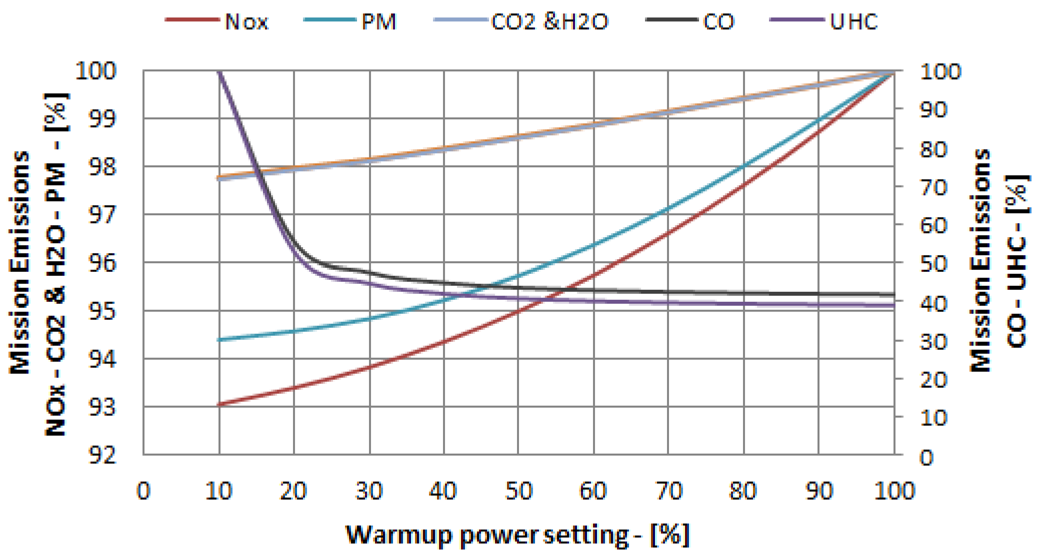

Figure D-2 Mission Emissions at different power settings

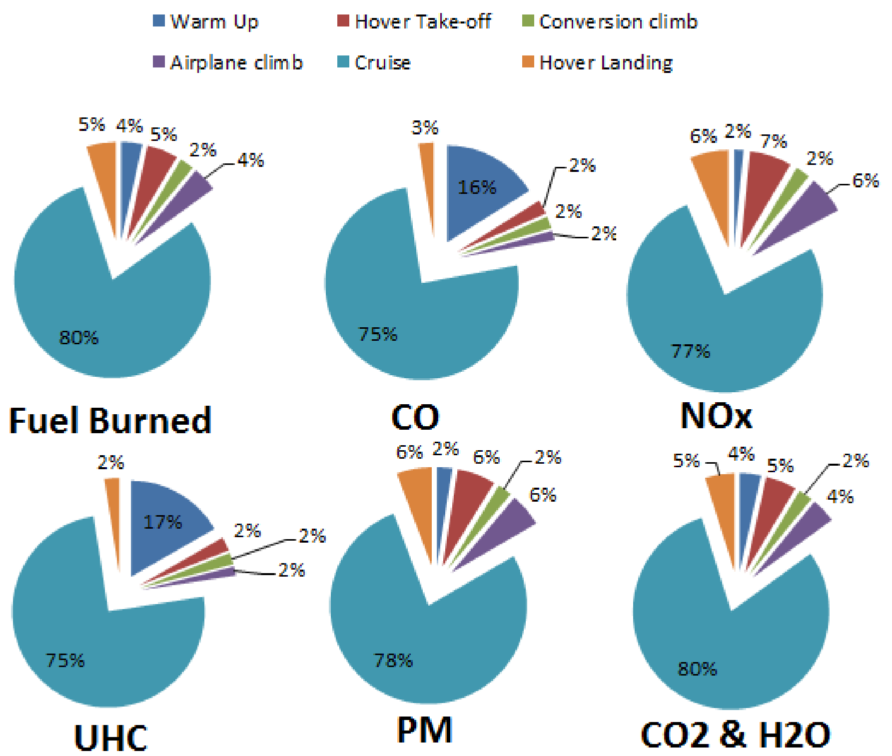

Figure D-3 Pollutant Emissions at different mission segment

Appendix E. Tilt Rotor Model 300 Information

This tilt rotor was develop by Bell Helicopter Company and conducted by NASA; it was a previous study of the best known XV-15

BASIC DATA

Aircraft Weight	
Empty Weight	6876 lb
Normal Gross Weight	9500 lb
Engine	2
Manufacturer	Pratt and Whitney
Model	PT6C-40
30-minutes rating (2 x 1150)	2300 hp
Maximum continuous Rating (2 x 995)	1990 hp
Proprotor	2
Diameter	25 ft
Number of blade per rotor	3
Solidity	0.089
Rotor blade area	43.75 ft^2
Wing span	34.2 ft
Wing Area	176 ft^2
Aspect Ratio	6.6

Appendix F. Additional expressions to calculate Noise in Hover

Davidson and Hargest (1965) from measurements of rotor noise in hover

$$L_{PN_{150}} = 10log_{10}\left(\left(V_{tip}\right)^6 A_b \left(\frac{C_T}{\sigma}\right)^2\right) - 36.7 \tag{F-1}$$

Schlegel, King, and Mull (1966) developed empirical expression equivalent to

$$L_{PN_{150}} = 10log_{10}\left(\left(V_{tip}\right)^6 A_b \left(\frac{C_T}{\sigma}\right)^2\right) - 42.9 \tag{F-2}$$

Stuckey and Goddard (1967) found from vortex noise measurements of a rotor on a whirl tower

$$L_{PN_{150}} = 10log_{10}\left(\left(V_{tip}\right)^6 A_b \left(\frac{C_T}{\sigma}\right)^{1.66}\right) - 39.9 \tag{F-3}$$

Also, these expressions can be scaled to other distances and elevation angles with

$$L_{PN} = L_{PN_{150}} + 20log_{10}\left(\frac{150}{d} \times sin(\varphi)\right) \tag{F-4}$$